

EFFECT OF SAFETY FACTORS ON TIMED HUMAN EGRESS SIMULATIONS

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ABSTRACT

This report covers the effect of safety factors on the time taken for humans to escape a building where fire has initiated. Monte Carlo simulation is used to determine the probability of failure to escape in a given fire scenario.

The simulations indicate that the safety factor is very influential upon the probability of failure to escape. The major effects upon egress are ranked in this order of significance; time taken for the occupant to decide to leave the building after hearing the alarm, the time until conditions are too hostile for human survival, and the time until the fire is detected. The occupant's travel speed to leave the building has such a low level of significance that it should be treated deterministically in future studies of this type.

Where a safety factor of two is applied there is a reasonable probability of failure.

ACKNOWLEDGEMENTS

I would like to acknowledge the patience of my two supervisors David Elms and Andrew Buchanan in my efforts to assemble the model and produce results from it.

I thank my family for helping me throughout my years of study.

To the Universe in which we live in, for providing more mysteries than man will ever be capable of solving with science.

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Nomenclature

Lognormal(x,y)	a lognormal distribution function with a mean of x and a standard deviation of y
M	safety margin
Normal(x,y)	a normal distribution function with a mean of x and a standard deviation of y
p	probability of failure in the limit state equation.
P_{target}	Target probability for failure.
R	supply capacity
R	regression correlation coefficient
S	demand requirement
SF	safety factor
t	time (s)
t_{esc}	time taken to escape from the point of ignition
t_{un}	time until untenable conditions occur after ignition
X_n	a component of random distribution.
α	t^2 fire growth rate

1. Introduction

How safe are the typical deterministic designs for human egress? How safe are they when a safety factor of two is incorporated? What happens to life safety when a safety factor other than two is used? How can life safety be determined? To determine the safety of escape route design, current design has to be examined. To examine current design methods a method of analysing human egress is required. How can life safety be examined? In terms of the probability of design failure or by the loss of life? This project determines a method for examining human egress. Then an examination of current design and the safety factors employed is performed.

1.1. Background for design of escape routes

Design of an escape route implies that the occupants of the building escape from the building before conditions threaten their lives. The time to leave the building must be less than the time to untenable conditions, so:

$$t_{\text{esc}} < t_{\text{un}}$$

where

t_{esc} = time taken to escape from the point of ignition

t_{un} = time until untenable conditions occur after ignition

We require knowledge of these times. When an escape route is designed, we do not have the knowledge to determine these times, so engineering judgement is used to choose deterministic values.

Time to escape is composed of some physical factors and numerous human factors. The factors are the time until the fire is detected, the time for occupants to respond to the alerting system, and so on.

The time until untenable conditions occur is determined by fire dynamics and untenable conditions. Untenability can be determined by the toxic effect of the fire environment on the occupants, the convective heat or radiative heat. In design the smoke layer height is typically used to mark untenability, which is when the smoke layer has gone below head height.

Due to the uncertainty attached to human factors, as well as uncertainty in detection, the design equations for egress contains a factor to counter the uncertainty (FEDG 1994):

$$t_{esc} \cdot SF = t_{un}$$

where

$$SF = \text{the safety factor} = 2$$

The origin of the safety factor appears to have no experimental basis. In design of an escape route this factor has the potential to be abused because of its multiplicative nature, when combined with the uncertainty associated with human egress. Designers can use a smaller safety factor than what is specified (FEDG 1994), whereas a smaller safety factor will increase the probability of design failure. The increase in the likelihood of fatality is examined in this report. The effect of modifying the safety factor has not been examined so a designer modifying the safety factor has no evidential support of what adjusting the factor will do.

Fire engineering design is performance based, so a performance model of human egress is required. This is where a quantitative risk assessment model can be useful, because it will determine the performance and can account for variables that have a distribution attached to them. Current design uses deterministic design values. Deterministic design lacks the knowledge of the distribution of the input variables, and does not have a probability of failure attached to it.

1.2. Objectives

The objective of this report is to determine what the probability of failure will be for differing safety factors. Failure is the failure to protect the life safety. All egress designs have a probability of failure. Therefore, finding an acceptable level of relative safety between the different safety factors will be determined. The safety factor is applied as a safety margin because the distribution of the total time taken to evacuate the building would be distorted if the safety factor were to be applied multiplicatively.

The approach taken to examine the safety margin is to use a Monte Carlo simulation approach to determine the probability of failure. Using a variety of input distributions that effect the total time taken for a person to escape from the building being examined. Untenability limits are determined from a deterministic physical fire model, FAST version 3.14. Three compartments are modelled in FAST: the room of fire origin, the room of occupant origin, and the corridor. The results of the physical fire modelling are used in determining the untenability time in the Monte Carlo simulation.

Limitations imposed on the fire modelling include assuming; that the room of fire origin, the window in the room of fire origin, the room of occupant origin, and the escape door from the corridor are open. The windows and doors that are treated as being open are for the ventilation in the FAST fire modelling. Occupant travel distance is a constant. The escape door is treated as a vent going to the outside, as is the window in the room of fire origin.

2. Review of existing literature

This chapter covers a number of papers that have contributed directly to the area of evacuation modelling utilising quantitative risk assessment methods.

For concepts on risk based design and decision analysis Ang and Tang (1975) is highly recommended. The risk based concepts in this report make use of the concepts in that publication.

Fire Code Reform Centre (1996) published Figure 1 in their Fire Engineering Guidelines. This is a system for deciding to escape with the consequences of this system detailed. A more simplistic model has been used in this project.

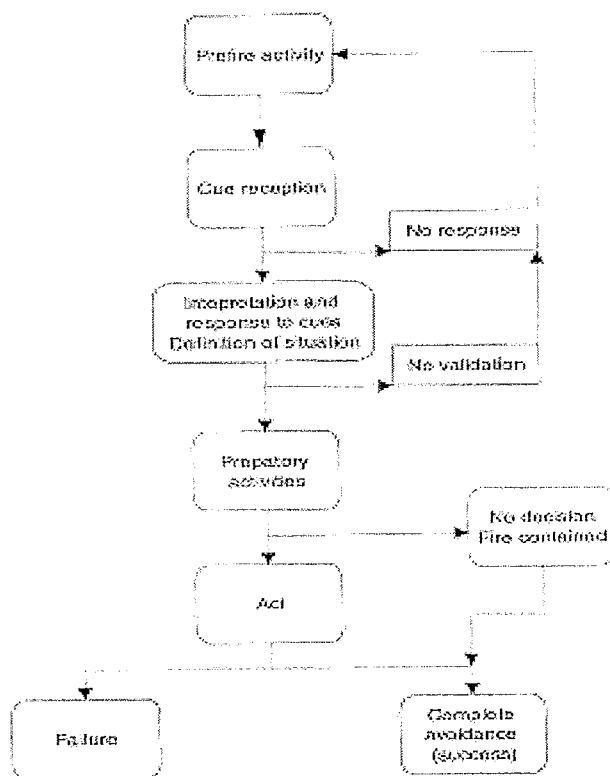


Figure 12.1 - Dynamics of Fire and Occupant Avoidance

Figure 1 System for decision to exit building with consequences, Fire Code Reform Centre (1996)

2.1. Fire Safety Design Based on Calculations

Uncertainty Analysis and Safety Verification

Magnusson et. al. (1995) gives an excellent overview of the current methods that can be applied in risk analysis.

The paper gives a list of the general fire safety sub systems present in a building. It then covers what factors will determine the available safe egress time (ASET), and moves onto an event tree that describes the different fire scenarios. The scenarios that could occur are based upon activation or failure of active and passive fire safety systems relevant to safe egress.

The next stage is the definition of a limit state equation for which failure is determined by the output of the equation being negative. This limit state equation gives time for smoke filling to head height (1.6m), detection time, response and behaviour times, and movement time.

Knowledge uncertainty and variability (stochastic uncertainty) are also defined. It is an important distinction where uncertainty has originated. This allows the definition of which components of variability can be reduced by knowledge, or if the variability is inherent in the variable being examined. Then the uncertainties are analysed.

The report covers all the available methods for risk analysis and where they are appropriate. This allows selection of the appropriate tool without time being expended on analysis which is incorrect for the problem being examined. An examination of available software is minimal, but the software examined is still available and useful.

Safety checking by the derivation of partial safety coefficients is detailed. This is a description of the influence of variables and how their influence can be determined. This leads to the output of a β -index value.

It contains a list of main building types for analysis, which is small and simple but does cover a large number of structures. These ideas can be easily adjusted to similar building types, if need be.

An example of one of the building types, places of assembly, is performed. This example includes awareness times and the probability of an exit being blocked. The exit blocking is simple, but reasonable. A calculation model is demonstrated and the input distributions and the values (mean and standard deviation) are shown. Some of the input values are not completely justified, but the values are not unreasonable.

Response surfaces for the different scenarios are designed, though the method for defining the response surfaces were not detailed. The response surfaces would generate, from the alpha value of the t^2 design fire, detection and untenability times. The response surface data used here originated from CFAST modelling. So, the time until untenable conditions occurring is developed from physical modelling.

Uncertainty analysis by five different methods was performed on the response surfaces and limit state equation defined earlier. The output from each of these methods was then compared. The output from each method was in the form of probability of failure.

This paper is very useful for understanding all of the available methods and covers an example of a large place of assembly. This paper is useful for both functional and theoretical purposes.

2.1.1. Awareness Time

Magnusson et. al. (1995) suggests an awareness time to be calculated in the following manner; if the occupants have a good view of the fire then a lognormal(10s, 5s) distribution is used. The lognormal function uses the first value as the mean of the lognormal distribution of awareness time, and the second value as the standard deviation of the distribution. If the occupants do not have a good view of the fire, and if the fire alarm is operating then a DETACT-QS time is used. If the alarm is not operating then 2 x

DETECT-QS is used. DETECT-QS is a quasi-steady state program for calculating thermal detection times. The program calculates the temperature at the thermal detector from quasi-steady plume equations. DETECT- t^2 uses a non steady-state equation for calculation of temperature. The equation used is for t^2 fire growth, which is a time based heat release equation. The t^2 equation uses time squared, multiplied by a selected constant (the α value) and the heat release at that time is calculated.

That method gives the time where awareness of the fire occurs but does not consider the time taken for people to hear the alarm until they make the decision to leave the building. DETECT-QS is only a quasi steady-state calculation, DETECT- t^2 would be preferred for the case of t^2 fire growth. The detection time calculated is only for thermal detection devices. So, this calculation does not take into account the smouldering fire scenario where a smoke detector would detect the smoke particles before the fire reaches a growth phase approximately equivalent to a t^2 fire.

2.1.2. Time until movement

Magnusson et. al. (1995) selected a movement time with a distribution of normal(300s, 300s). This is an extremely flat distribution, with a mean of 300s and a standard deviation of 300s. Using a distribution with such a large distribution of times is likely to make the probability of failure more likely and reduce the safety index. The large knowledge uncertainty that is contained in this distribution will make the time available to escape from the building, in a large number of cases, no time or negative time to escape. That will increase the number of failures in Monte Carlo simulation, the equivalent in the usage of β -indexing is a reduction of the β value. A negative time for movement does not make practical sense, therefore we assumed that this distribution is truncated to prevent the occurrence of negative outputs (though this is not stated in the paper). This is an area that requires a significant level of investigation to reduce the knowledge uncertainty.

2.1.3. Doors

Magnusson et al (1995) utilised engineering judgement for the likelihood of an escape door being blocked, unfamiliar, and if the fire is close to the door.

The movement times for escape were based upon the flow that was possible through doorways.

2.1.4. Type of Occupancy

Magnusson et al (1995) focused on places of assembly, health care facilities, and hotels. Thus the number of occupants is expected to be large (in the region of 600 or more people).

The area being investigated by Magnusson is a large room with an exit or multiple exits.

2.1.5. Results

The conclusion reached was that the underlying uncertainty involved in the calculation meant the common design criterion of $\beta = 2$ could not be met.

That conservative choice of distributions may have led to the calculated safety levels being low.

Figure 2 shows the failure percentage of the eight scenarios used in their study, these results are for a large stadium with or without alarms and sprinklers.

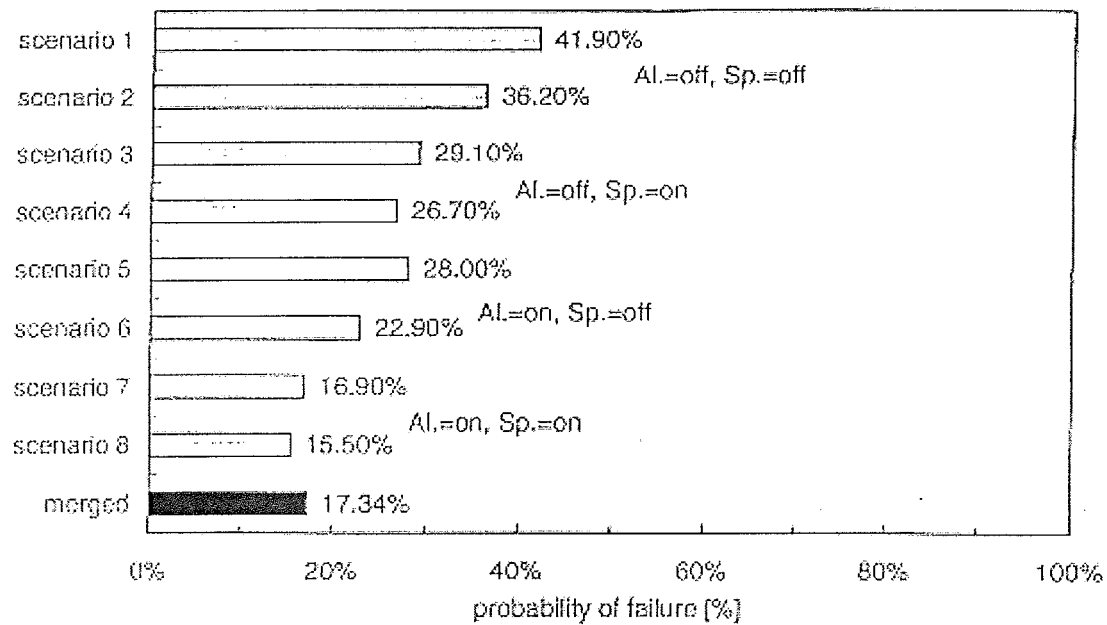


Figure 2 Probability of failure for 8 scenarios using monte carlo simulation also showing merged results from an event tree (Magusson et. Al. 1995)

Figure 3 shows the safety index determined by the First Order Second Moment (FOSM) method, the β values are for the exact scenarios shown in figure 1.

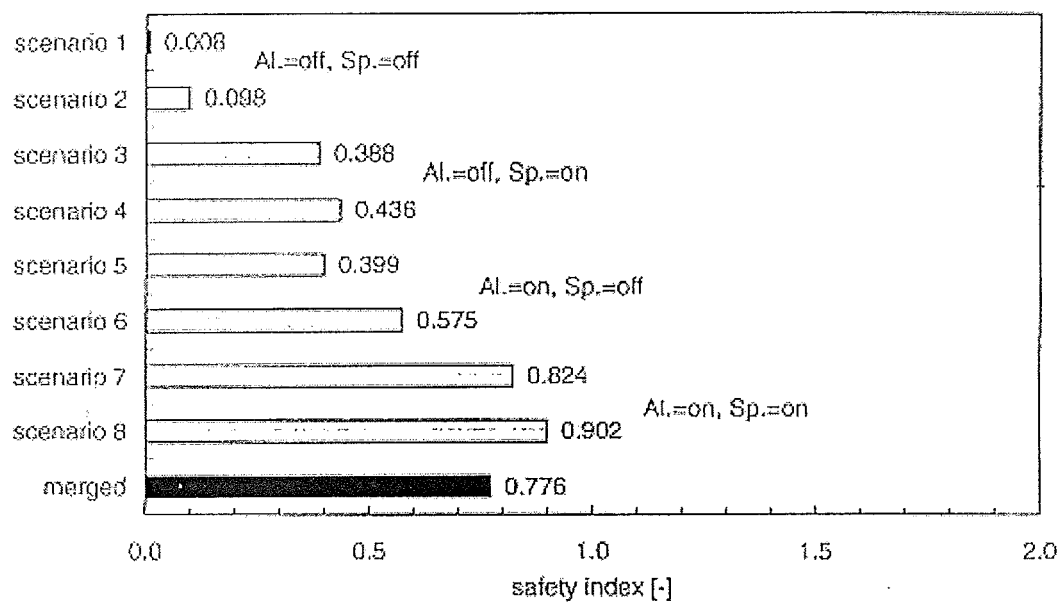


Figure 3 Safety index beta for 8 scenarios using monte carlo simulation also showing merged results from an event tree (Magnusson et. al. 1995)

2.2. Fire Safety Risk Analysis of a Hotel

Frantzich (1997) is a case study of one of the building types specified in the report by S. Magnusson et. al. (1995), specifically a standard hotel building.

The report specifies a corridor with standard hotel rooms all with doors leading into this corridor. Each end of the corridor has a stairwell, providing two independent exits.

Details of the probability of fire per year in a hotel are defined. Risk is described from two standpoints which are both are useful in deciding what the acceptable risk to a person may be defined as. The first is individual risk. Individual Risk is defined as the risk to a person per year. Thus, the time spent in the hotel should not exceed this risk level. The other approach is that of Societal Risk. Societal Risk is defined as the risk of a multiple fatality fire.

The method of comparison for societal risk is on an F-N curve. An F-N curve has on one axis the probability of failure. On the other axis it has the number of fatalities. Some European countries have some defined lines on the F-N curve which should not be exceeded in design. Something that can be determined from an F-N curve that a risk calculation will not show is the likelihood of a large number of fatalities. Where there is a large number of fatalities, even though the risk (probability multiplied by consequence) is acceptable, this may be an unacceptable loss to the perception of the general public.

Figure 4 shows a dotted line, which is the mean of their data. The hand drawn line ranging from 10 to 100 people being affected and from the point of 10 people being affected to the probability of 10^{-5} is the Dutch limit. This line should contain the data shown (the black line). The 80 %-tile shows that their analysis of a hotel, in 20% of cases, fall outside of the Dutch limit. They pointed out that the average case in their simulations were inside the Dutch limit. So the hotel analysis meets the Dutch limit.

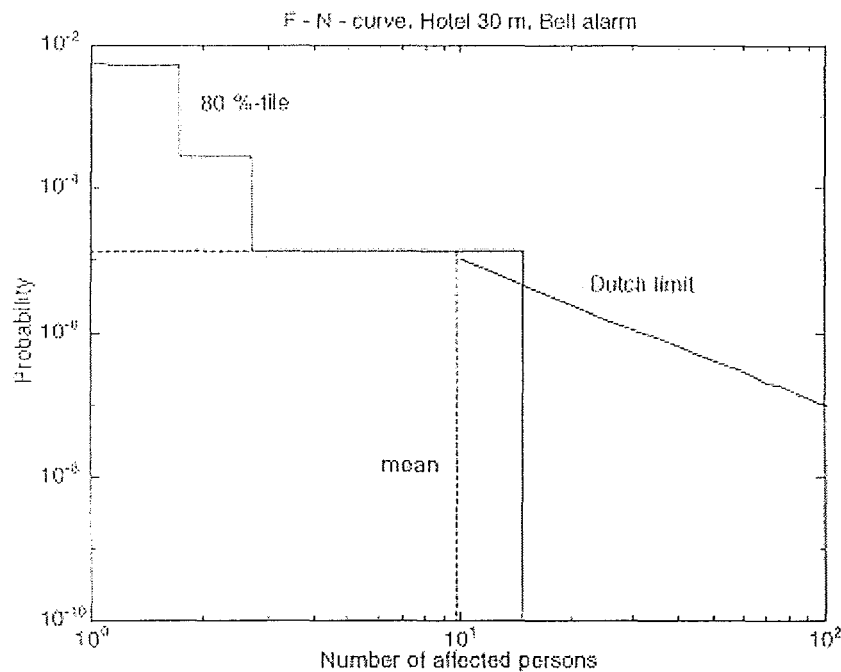


Figure 4 Typical F-N Curve with the Dutch Limit Imposed (Frantzich 1997)

Practical details of implementing individual and societal risk methods is then covered in considerable detail.

Modelling surfaces are then stated, but the method that led to their creation is not explained in detail. The response surfaces are stated to have come from physical models.

2.3. Fire Safety Risk Analysis of a Health Care Facility

Frantzich (1996) covers risk analysis techniques applied to three Swedish Health Care Facilities. The detailing of a health care facility is of a different style compared with the other previous methods.

Due to the complexities inside health care facilities there are an extensive number of possible scenarios. The complexity was so high that only one of four main branches was analysed in depth.

Probability of fire was determined by specific data from individual facilities.

The fire safety calculations were performed in a manner similar to the hotel corridor scenario. Fire growth conditions were based upon parametric equations utilising t^2 fire growth rates. Failure surfaces were determined from CFAST modelling. The model CFAST is produced by the National Institute of Standards and Technology and is freely available. The model performs calculations based upon zone modelling of compartments and utilises t^2 or user defined heat release rates. Detection times were determined from DETACT- t^2 , then turned into a spreadsheet equation, in a similar manner to the CFAST modelling.

Movement times incorporated the response times based upon staff reaction times. Event tree conditions include the mobility of patients, as this is a significant factor in a hospital environment. Differing levels of mobility were accounted for and the staff resources required during the evacuation were accounted for.

The results were based upon individual risk to a patient compared with normal risk of death faced by individuals. Limitations in the results and performance were clearly stated. The model was only for one hospital ward. This is useful for probabilistic design purposes, but not necessarily for general conclusions about the fire safety of health care facilities.

2.4. Risk Assessment of Timberframe Multistorey Apartment Buildings.

Proposal for a Comprehensive Fire Safety Evaluation Procedure.

Magnusson and Rantatalo (1998) examines risk assessment methods like ranking systems, checklists, narratives and probabilistic design.

A policy-based risk ranking system is implemented. The general system used is specified in the SFPE Handbook. Of the papers available this appears to be the only one which has implemented this method in a practical manner for fire safety engineering.

There are considerable drawbacks to this approach. The weighting of the parameters that are detailed in the evaluation are determined by expert opinion. Probabilities calculated from this method do not originate from physical fire modelling.

The Gretener method for risk ranking is examined and compared with existing methods. Some probabilistic methods are mentioned including FiRECAM, CRISP II (the previous two titles are risk assessment packages for fire safety), and quantitative risk assessment. No practical information for the use of these is stated.

This paper examines a number of topics lightly but contains no substantial quantitative risk assessment information.

2.5. Uncertainty in smoke transport models.

Lundin (1997) contains physical smoke modelling that was performed, then modelling of an identical compartment in CFAST modelling. The results compare the differences between a real compartment and the virtual compartment.

This experiment demonstrated a mean over prediction of temperature by 25-40%, and an under prediction of the measured interface height by 10-40% in the compartment. It is stated that these differences are average and that a conclusion cannot be drawn because of the size of the random error involved. Statistical analysis was performed.

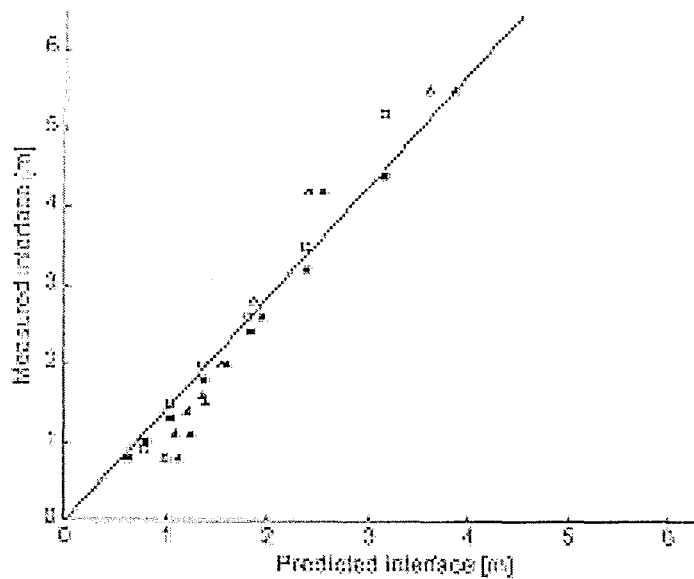


Fig 6.3 Scenario V1, the tests and the weighted regression line

Figure 5 Predicted interface compared with measured interface (Lunden 1997)

Figure 5 shows that the predicted interface height from CFAST is further from the ground than in the experimental tests, in the late stages. This means that a layer height prediction of 1.5m from the ground happens earlier in experimental tests than the modelling. In the early stage, where the interface is higher, the measured interface is further from the ground than the modelling.

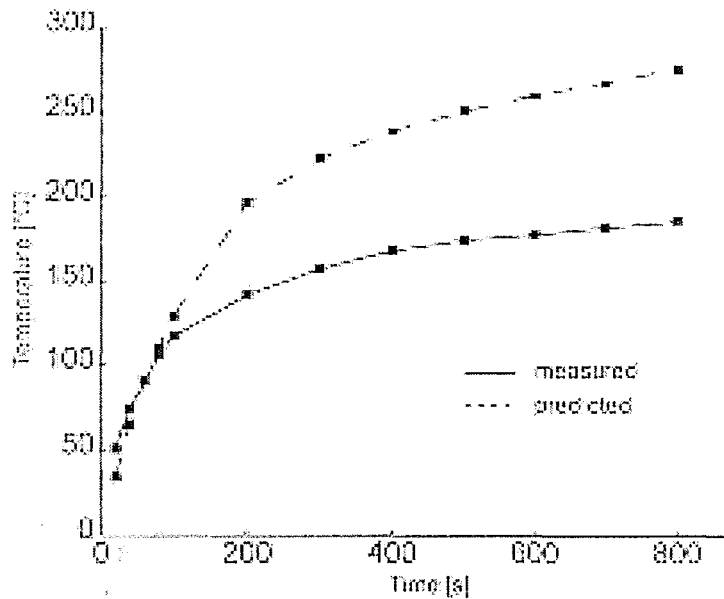


Fig 3.3 'V3-set 9-room 2', T_{ce} and T_p plotted against time

Figure 6 Measured and predicted temperatures versus time (Lunden 1997)

Figure 6 displays a more rapid increase in temperature in the modelling than in experimental work. This means that an untenability prediction based upon temperature will occur before the temperature condition is likely to occur.

This paper does point out the large amount of random error contained in the CFAST modelling which is useful to understand when performing such physical modelling. Although the version of CFAST that was being used was not stated, but appears to be an earlier version. Depending on the revision the physics applied in the model they were using may be different from the current version. Despite the large amount of random error some of the modelling performed in papers contained in the literature review make corrections based upon this document in their modelling.

2.6. The Swedish Case Study.

Different Fire safety Design Methods Applied on a High Rise Building.

Jonsson and Lundin (1998) compares current fire safety design with the existing prescriptive building guidelines. There is only the one scenario used in the building

design, but different approaches to designing the same building to this level of functionality. Then describes a risk based verification method performed on this building, there is a note of a risk based design method that is not included in this report. It is available in another report that we have not studied.

Swedish building regulations are detailed in their current structure.

All the design methods are specified in reasonable detail. The risk based verification is based upon an F-N curve derived from an event tree. The design criteria for this type of design is specified by a maximum F-N curve marked on their diagram. This line puts a maximum cap on what probability is maximum and for each probability what the maximum number of fatalities can be. The integral of the line's area would have a total risk that would exceed an acceptable level. The combination of a risk calculation and the F-N curve method would be valuable for design purposes. The detail required is the level of individual risk and a calculation of societal risk. Performing an analysis to this level for this is very resource consuming.

The building design is detailed to the standard of a real building design. The design fires are specified, and all evacuation data is stated for each scenario, especially values of reaction times. Some values appear from the BSI guide for the probability of failure of the different fire safety systems examined, some calculated, and manual evacuation and no alarm reaction times are assumed. The available staircases in each scenario are specified in six scenarios and five engineering design methods.

A cost comparison is performed which is interesting. An interesting cost comparison is performed where fire safety engineering generally comes out cheaper than the Standard Swedish methods. There is no evaluation of the comparative safety of each of these design, although that is subjective.

2.7. *Draft Technical Report.*

Part 1: The application of fire performance concepts to design objectives.

Standards Australia (1998) have included a chapter on probabilistic design, which is an advancement in standards. This report states a generalised fire safety design process including safety objectives, codes of practice and the type of data required.

The major problem with this report is that it lacks practical content. The report does not cover probabilistic design for human egress. The report examines a general idea for establishing the overall level of uncertainty for allocating an appropriate safety factor, but it does not state what criteria would be appropriate. It does however put the safety factor applied to professional judgement and peer review with an informed understanding of the limitations of the chosen scenarios, models and data.

This document states that “probabilistic procedures often lack the technical detail and the full use of fire science fundamentals found in the deterministic procedures.” This report does not cover probabilistic risk assessment (PRA) methods that require the use of fire science and does not include Monte Carlo design.

In Annex D, of the draft report, a probabilistic design equation that covers the number of deaths in a given fire scenario does not make sense in terms of probabilistic risk assessment. The number of deaths in a given fire scenario will be a part of a calculated distribution. This equation can only make sense if incorporated into a risk equation, where this equation is the consequence. A probability of that number of fatalities is required and then the output from this would be an FN-curve. This would be an examination of societal risk, but no reference is made to societal risk, nor to individual risk. The equations stated do not appear to be practically implementable.

This document needs further clarification and probabilistic risk assessment concepts to be applied to the probabilistic design section.

2.8. Conclusion

There are a number of methods for risk assessment available. These methods give a probabilistic assessment of the likelihood of failure, and utilise probabilistic parameters. It is necessary to have data to define the parameters, therefore it is necessary to know what data is available for well-defined classes of buildings (Magnusson et al 1995).

For design purposes it is necessary to link risk calculation procedures and the design format (Magnusson et al 1995). Therefore knowledge of current design procedures and finding a link in a risk assessment methodology to evaluate the risk of the design is valuable.

The different fire safety systems for the purpose of egress in a building are broken down into six sub-systems (Magnusson et al 1995). These systems are the;

- calculation of fire growth in the room of fire origin
- calculation of smoke spread to other compartments
- calculation of spread of fire to other compartments
- calculation of detection and activation of active systems
- fire brigade communication and response
- calculation of evacuation times

3. Simulation modelling

This chapter examines the components required for a simulation model. For a model that uses a limit state equation (for determining failure) inputs are required to determine if the limit of the equation has been exceeded or not. This gives the binary determination of failure or success.

Reasons for the failure of an evacuation design

The design failure condition of escape is the environment becoming untenable. Failure occurs when the following time based variables exceed the time until untenable conditions:

- Alerting time (or detection time)
- Time for activation of warning system
- Decision making time
- Travel time

The time taken for occupants to evacuate (t_{esc}) in the modelling in this project is the sum of; alerting time, time for activation of warning system, decision making time and travel time.

Understanding the former variables, with a formalised methodology for egress design, should reduce the likelihood of a deficient egress design.

This project has one limit state inequality.

$$t_{un} - t_{esc} \leq 0$$

Where t_{un} = available egress time until untenable conditions occur

t_{esc} = time taken for the occupant(s) to evacuate

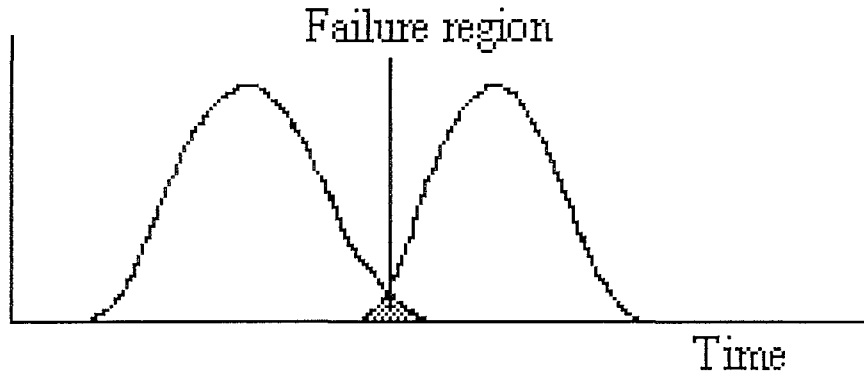


Figure 7 Distribution for escape time and untenability time.

Figure 7 shows two distributions with an overlap. Assume one distribution is the distribution of the time to untenability and the other is a distribution of egress time. The bottom axis is time taken. Where the two distributions overlap this is the failure region, which means failure is possible. This research has utilised this idea, but has used a fixed untenability point, which gives the failure region. This research's egress time distribution is composed of three input distributions including travel velocity, detection time, and decision making time.

So what is a deficient egress design? When designing for egress the objective is to avoid the failure condition from occurring. The failure condition is that of exceeding the limit of the limit state equation.

3.1. Determination of failure

This project has one limit state inequality.

$$t_{un} - t_{esc} \leq 0$$

Where t_{un} = available egress time until untenable conditions occur

t_{esc} = time taken for the occupant(s) to evacuate

When the inequality is exceeded then failure of the equation occurs. The failure means that the occupant(s) remaining are trapped, incapacitated or dead.

Analytical models that only have one limit state equation have two risk prediction methods available, the First Order Second Moment (FOSM) approach and Monte Carlo simulation.

For this project a scenario has been chosen. The scenario is based in the office level of a University of Canterbury Building. It is assumed to be a single story building to meet the requirements of the Building Code Handbook (Building Industry Authority 1995).

This scenario was simulated using a Monte Carlo simulation. The reason for Monte Carlo approach being used is the simplicity of performing a large number of iterations. The iterations allow an output distribution to be formed from the input distributions and the limit state inequality. From the output distribution the probability of failure can be determined, which is the failure point of the limit state inequality (when time remaining to escape is zero). Using the FOSM approach would require the usage of a mathematical methodology, this is prone to human error, and it is difficult to make small changes. Monte Carlo simulation using the @RISK package in Excel allows small changes to be made, and a large number of differing distributions to be utilised in the limit state inequality. The simulation will also demonstrate the number of times the limit state inequality's failure condition was met. Thus a failure probability can be determined without mathematical analysis.

These simulations were based upon physically derived inputs.

The inputs used are:

- Detector activation time
- Untenability time (from FAST modelling)
- Time until conditions become untenable
- Reaction time
- Travel speed

Knowledge uncertainty and variability

There are two types of uncertainty that a statistical population contains; knowledge uncertainty (that is due to a lack of knowledge about the particular system, Type B uncertainty), and variability (stochastic uncertainty, randomness, Type A uncertainty).

Knowledge uncertainty occurs where random or systematic error occurs

Variability can be reduced by increased knowledge of the random variable and approaches to reduce the variance (like increasing the sample population, etc). This is where latin hypercube sampling (rather than random sampling) is useful in Monte Carlo simulations.

Latin hypercube sampling breaks the output of a simulation into discrete outputs. In this way stratification of the model outputs gives separation of variability from knowledge uncertainty. The effect of this on Monte Carlo simulation is the reduction of the number of iterations that must be used to achieve convergence of the outputs.

3.2. Monte Carlo simulation in egress design

Monte Carlo simulation is generally a system described by a number of random distributions. A computer is used to generate the random numbers that fit these distributions. Where a large number of random numbers are generated characteristics of the system can be examined. The accuracy of the simulation is generally improved by an increased number of iterations. The output(s) can be described as distributions or particular values or ranges of outputs can be examined. For example, where an egress design fails to provide enough time to escape, the number of times the escape fails can be simulated by a Monte Carlo simulation, or where a structural members fails to support its load during an earthquake or fire.

When utilising the risk analysis approach of Monte Carlo simulations there is always a probability of failure. Failure must be a set condition with definition, which is the purpose of the limit state equation. A particular concern is what is an acceptable level of

failure. The acceptable level of failure is a trade off between the risk to life safety, and the cost of implementation of safety systems.

When examining the acceptable level of failure. Society's perception of what is acceptable must be evaluated.

The probability of failure in this report is conditional on the environment specified in each scenario occurring. Therefore, a particular fire scenario must occur with the particular ventilation conditions, and room dimensions. The probability is also dependent on the time taken to escape and the detection time. There is also the factor of knowledge uncertainty that contributes to the probability of failure. Knowledge uncertainty will increase the probability of failure through the lack of knowledge about an input distribution (like decision making time), this will give probabilities of failure that are more than the actual real world probabilities.

4. Definition of Risk

This section defines the risk that is being calculated and the limitations of this approach. An alternative approach is acknowledged but that method has a higher level of difficulty in determination and evaluation of the inputs, as well as what the acceptable output of that method would be.

4.1. *Risk in fire safety engineering design*

Risk is defined as:

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

Where risk is applied to fire safety engineering the consequence is the ‘damage’ caused by the fire. Where damage is looked at in terms of property loss, or loss of life. The probability is the likelihood (ie, on an annual basis, or the lifetime of building/person) of that consequence occurring.

Risk can be defined as probability of a fire per year, deaths per year, or damages defined in monetary values per year.

Distinction must be made between calculated risk and perceived risk. Public perception can differ substantially from the calculated risk. Social perception of acceptable risk is based on perception, rather than calculated figures. Differentiation between voluntary and involuntary risk has to be made. People will accept higher levels of risk to themselves if they perceive the advantages of the activity they are engaging in to be worth the risk (Franzich 1996).

In this research the consequence is the conditions either in the room where the occupant is or that particular individual’s escape route becoming untenable. Failure occurring means one of the following states occurring; the occupant is trapped, incapacitated, or is dead. The probability of failure, in the Monte Carlo simulations in this report, is the proportion of simulated escapes that fail. Failure is determined by a limit state equation,

which has a failure limit based upon, whether there is enough time to escape or not. The simulations that exceed the limit of this equation determine the failure probability

4.2. Risk

Individual Risk is the probability that the undesired consequence will affect that particular person. The level of individual risk alters as the variables in the simulation are altered. Changing of door states (open or closed), ventilation sizes, door widths, number of doors, location of fire, and the many other variables that exist in the real world system of a building all affect the individual risk.

Society wants each individual to have a certain level of risk to life. This level of risk (or safety) limits the level of risk the individual is exposed to.

The likelihood of major or catastrophic failures, which have a large loss of life, has considerably lower probability of failure than individual fatalities. These catastrophic failures must still have the same level of risk as individual risk.

Societal risk takes the number (or distribution) of fatalities into account. The consequence in this case is multiple fatalities. The probability is of the likelihood of a particular number of fatalities occurring, and is evaluated for all fatalities.

The practical calculation of this level of risk is very work intensive, and requires complete risk analysis of every component of human society. This level of data collection and analysis is too work intensive to be realistically considered. Information in many areas would have extremely high knowledge uncertainties as to defeat the purpose of the calculation.

However, this approach can be applied to whole buildings if not only the risk to the individual is calculated, but if the risk to multiple individuals is performed. This would entail the failure event containing information on the number of fatalities as well as the

failure occurrence. This does not fully calculate societal risk, but the societal risk to the individual could be calculated for the time that is spent in the building in question.

This report does not calculate societal risk. Individual risk is calculated instead. The individual risk calculated is for a given scenario occurring, for which the probability of that scenario occurring has not been calculated to determine that actual individual risk.

5. Risk Methods

5.1. *Risk Ranking*

Risk Ranking systems currently exist for Hazard and Risk Assessment. These systems are based upon expert opinion and existing knowledge of risk to life (Watts 1995). Values are assigned for variables for particular buildings. The values obtained give the building a particular rating on a ranking system. The numbers used for ranking are not necessarily indicative of the actual probability of fatality. These systems also place the classification of life safety into discrete categories.

5.2. *Narratives*

The earliest form of risk assessment are narratives. Which are simply an observation that something can cause harm, like fire (Watts 1995). Such observations do not quantify what level of danger exists. A narrative will convey that something should be avoided. This does not necessarily show how to avoid the danger. A narrative is still used in egress when one occupant conveys to other occupants that they should evacuate a building because it is currently on fire.

5.3. *Checklists*

Checklists identify important features for safety. However evaluating a particular building with a checklist will not necessarily determine a particular level of safety. The list does not necessarily allow the flexibility to design a building for life safety in a cost-effective manner (Watts 1995).

Using checklists helps in fulfilling recommendations of safety practices. It does lack the ability to quantify the risk, and can be impractical in new or unusual systems that the checklist is applied to. Check lists are advantageous by their simple design, which can allow a person with minimal training.

5.4. Probabilistic Methods

Probabilistic methods have become more sophisticated due to the increase of available data and mathematical techniques. These methods allow the manipulation of fire safety variables according to recognised theory. Simulation and stochastic modelling are useful methods to analysis the effect of variables, and the effectiveness of fire safety scenarios (Watts 1995).

These methods can be slow to calculate and are prone to human error. When designing something by a probabilistic method and it does not meet design criteria, there is a large amount of work to recalculate the new design. These methods are advantageous because of the quantitative output from the methods.

5.5. Safety index β -methodology

This methodology is a capacity/demand based methodology. This is where demand and supply have distributions that overlap in a region, which is called the failure region.

$$M = R - S$$

Where M = safety margin

R = supply capacity

S = demand requirement

If R and S are random distributions then M is also a distribution.

The most probable failure point (probability of failure) is easily determined by the First Order Second Moment (FOSM) method. Unfortunately, the FOSM method gives no indication of the distribution of output. It does quantify the risk into a safety index.

5.6. Monte Carlo Simulation

Monte Carlo simulation can be used to simulate a scenario in a probabilistic environment. The simulation requires probability density functions for inputs. The probability density functions can be in the form of a normal distribution, although many other distribution types are possible.

For engineering using a limit state equation is useful. If you have a steel beam that will fail at a certain loading and the probability of the loading is known. Then the limit state equation will fail by its limit being reached or exceed. A simulation study of this type will give the probability of failure but a distribution of that failure can be determined.

Usage of computer packages like @RISK allows statistical analysis. This allows the determination of which variables have the most effect of contributing or reducing the likelihood of failure. Unlike analytical techniques, the input variables can be easily altered to produce more information about the failure distribution or probability.

There is a distinction between two types of Monte Carlo simulation (Magnusson 1995). Simulation without making a distinction between knowledge uncertainty and stochastic variability (inherent variability).

6. Modelling

The approach taken and values/distributions used in the modelling are defined in this chapter. Every input that has been used the scenario modelling is noted and described here. The limit state inequality is defined. The methodology applied is systematically listed. The actual usage of the methodology is described.

The modelling environment is detailed, including all the distributions. The physical modelling dimensions are shown, along with the tenability limits applied to the scenarios. The layout of the building is shown with the configuration of the environment and the occupant.

6.1. *Limit State Equation Target*

Design usage of the limit state equation will have to be less than a specified target probability.

$$p(M(X_1, \dots, X_n) \leq 0) < P_{\text{target}}$$

$p(f)$ = Probability of failure in the limit state equation.

M = Safety margin.

$X_{1..n}$ = Random variable.

P_{target} = Target probability for failure.

Currently there is no defined target for probability of failure in New Zealand. The comparisons in the modelling results are relative to the other modelled scenarios. Only the following section of the limit state equation target is used:

$$p(M(X_1, \dots, X_n) \leq 0)$$

6.2. *Methodology*

- 1) The time to untenability must be determined:
 - a) The room configuration being modelling is selected.
 - i) The door state is defined for the room of fire origin. Whether it is door or closed.

- ii) The room height is defined. This must be accurate for modelling.
- iii) The floor area is defined. This must be accurate for modelling.
- iv) The vent areas and the height from the floor and total height must be defined.

These also need to be accurate for modelling.

- b) A FAST or CFAST simulation must be run on this building configuration.
 - c) The output from the model must include relevant data for determination of untenable conditions. For example, if a Fractional Equivalent Dose (FED) is being calculated then species concentration must be switched on for the output.
 - d) Process the output to determine the time when conditions have become untenable.
 - e) This will give the time for the corridor becoming untenable. This is the area that the occupants are expected to be inside of while evacuating the building.
 - i) An exception is where the room of fire origin is closed. Some way of calculating door burn through would have to be used. This type of modeling has not been covered in this research.
 - ii) If the door burns through or a window breaks in the time scale of evacuation then this would need to be simulated and vents adjusted. In this model the ventilation has been assumed to be static.
- 2) The total time for an occupant to escape must be calculated. In this research one occupant with a fixed travel distance has been used. This calculation could be performed on multiple people with differing travel distances, then the probability of multiple fatalities could be calculated, but this is not covered in this research. This is the calculation method:
- a) Detection time is calculated.
 - b) Decision making time for the occupant is calculated.
 - c) The average travel velocity is calculated.
 - d) These times are added. The total time is the time taken for this occupant to escape in this particular simulation. This is the total time taken to escape (t_{esc})
- 3) The total time taken for escape (t_{esc}), from (2), is subtracted from the time until untenable conditions occur (t_{un}), from (1). This is the time available after escape. The limit in place from the limit state inequality causes the following outcomes from the simulation:

- a) If the time available after egress is less than or equal to zero, then the failure condition has occurred. The occupant can be considered dead, incapacitated or trapped.
 - b) If the time available after egress is more than zero, then the failure condition has not occurred. The occupant has escaped the building safely.
- 4) The output from the simulation package is used to determine the probability of failure. Which is the probability of zero time available after egress. If the probability of failure is not acceptable then the design must be altered until it is. This determination is not made in this research. Currently the values are compared in a relative manner to their equivalent safety factor or safety margin.

6.3. Usage of methodology

The time to untenability is determined by geometrically defining the physical modelling area. The definition of height, ventilation size and design fire growth rate is important. The door state (whether it is open or closed) must be noted.

A CFAST simulation is run on the configuration. Untenability conditions must be selected. The output from the model must contain the relevant information for meeting the untenability condition.

The untenability time becomes one of the inputs into the limit state equation, where the untenability time is t_{un} . The untenability condition must be for the compartment that the occupant will be in at that particular time. For simplicity in this modelling the untenable conditions are always determined in the corridor.

The total time for the occupant to evacuate from the building must be calculated from the detection time from ignition, the time taken to decide to evacuate the building, and the distribution of travel velocity. These times are added together to determine the total time taken to evacuate the building. The decision making time includes any pre-evacuation activities that occur after the alarm, and it is the time before actively attempting to leave the building. The time taken to evacuate the building is taken as a constant travel

distance, but uses a travel velocity distribution to determine the time taken to leave the floor. Once the occupant has left the floor they are assumed to be in an environment protected from the effects of smoke for long enough to leave the building. Therefore, the occupant is considered safe once on the stairway, and the stairway is assumed to be safe and unhindered for egress.

Once suitable inputs for the distributions of detection time, decision making time, and evacuation speed have been defined then the Monte Carlo simulations can be run. The output of these simulations have a distribution of time available for escape, and where that time is zero on the Cumulative Distribution Function (CDF) of the time to escape, that is the probability of failure.

6.4. Modelling environment

6.4.1. Building

The building used in the modelling is a partial area of one floor level of the Civil Engineering building at the University of Canterbury. The particular section isolated would be separated by automatically closing fire doors upon detection of a fire. The dimensions are similar but not exact. The doorway leading from the corridor goes into a stairwell that has connected smoke stop doors and fire rated walls. In the context of the simulation the stairwell is considered to be safe from fire. In building design this is unacceptable, except for mobility impaired people for which this is a refuge until rescued.

The floor consists of a long corridor with a number of equally sized rooms connected to the corridor. All the doors are assumed to be closed in the event of fire. Except for the room of fire origin. This door is assumed to be open because of the time scale of the simulations, where the time scale for untenable conditions is short compared with a door burning through.

Figure 8 is a layout of the floor modelled. The circle is the occupant, the capital **F** is the room of fire origin, and the X on the left hand side of the corridor is the exit.

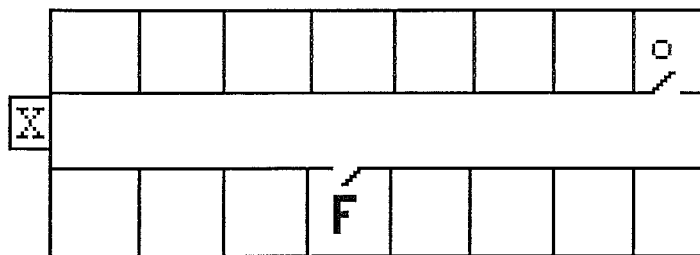


Figure 8 Floor plan of the building floor modeled

This floor complies with the New Zealand Building Code Handbook, annex C (1995). When the purpose group is WL (Working, Light hazard) as a single story building the required fire resistance rating is F0 (no fire resistance rating). A fire safety design would compartment the rooms off with a fire rating, that would include door closers. This would change the physical modelling set up. Modelling of rooms with closed doors has not been performed because of the added complexities associated with modelling door burn-through, and fire spread.

6.4.2. CFAST Modelling

The rooms and corridor have their surface materials defined as; gypsum for the walls and ceiling, and plywood for the floors. This is an assumption of typical building materials. Table 1 shows the dimensions of the compartments that were used in the FAST modelling.

Room	Depth (m)	Width (m)	Ceiling Height (m)
Fire origin	2.5	3.6	2.5
Other rooms	2.5	3.6	2.5
Corridor	2.2	20	3

Table 1 Physical dimensions of the rooms modelled

Table 2 shows the ventilation used on the compartments for FAST modelling.

Room	Width (m)	Height (m)	Connects to
Standard room	0.95	1.9	Corridor
Room of Fire Origin	0.95	1.9	Corridor
Room of Fire Origin	1	1.1	Outside
Corridor	1	2	Outside

Table 2 Vent sizes for compartments

6.4.3. Untenable Conditions

The evacuation of the occupant(s) from any of the rooms on the floor and from the corridor into the stairway must be completed before conditions become untenable. If not, they are trapped or dead.

Toxicity assessment of combustion products was done by fractional equivalent dose (FED) (Purser 1995). The species concentrations come from the output taken from FAST. None of the carbon to hydrogen or other chemical ratios were altered in FAST. The FED level considered untenable was set to 0.25 FED. Modelling papers (Frantzich

1997) set the FED to 0.5. The value of 0.25 was selected by judgement to be a level that would ensure that the occupant would survive.

Convective heat in the lower layer (or if the upper layer has dropped to 1.5m) of 65°C was considered untenable (FEDG 1994). Radiative heat, where the upper layer reaches 200°C was considered untenable.

Table 3 displays the limits imposed for untenable conditions to occur. If any one of these conditions is met in the corridor compartment then it is considered untenable. Fractional equivalent dose (FED) was only measured for the upper layer. The FED measurement of 0.25 is not typically used in research papers (usually 0.5) but was assumed that the occupant would have little chance of surviving if the FED went above this. The radiative heat limit is only measured by the upper layer (FEDG 1994). The convective heat was measured from the lower layer until the layer height had dropped to 1.5m. In the vast majority of simulations, the convective heat was the condition that would be met.

Untenability condition	Condition limit
Fractional equivalent dose	0.25
Convective heat too high	65°C
Radiative heat too high	200°C

Table 3 Untenability limits

It is likely that the usage of these numbers will produce results on the safe side of the fire environment. This may bias the probability of fatality in the results. So an alternative set of numbers is used in the sensitivity analysis section to compare how choosing such numbers will effect the probability of failure. The alternative numbers are chosen based upon the known limits of exposure that will cause a fatality. This will be the best knowledge that we currently have, which is ultimately limited by differences between individuals. What may affect one person may not affect another, depending on a variety of human variables.

6.4.4. Specification of design fire

Three design fires were chosen to examine the difference in probability of death. A slow, medium and fast fires were chosen to use for the α^2 design fires. Where the α values are as follows:

Slow: $\alpha = 0.00293 \text{ kW/s}^2$

Medium: $\alpha = 0.01172 \text{ kW/s}^2$

Fast: $\alpha = 0.0489 \text{ kW/s}^2$

The relationship of this type of fire determines the rate of increase of heat release from the fire. Heat release from the fire is time dependent. When this heat release curve is used with a fire modelling program such as FAST other physical factors are calculated. Ventilation becomes important and ultimately (in the case being examined here) limits the heat release from the design fire. However, untenable conditions are likely to occur, by the imposed design limits, before any such limiting of the fire is a major effect.

6.4.5. Time to untenable conditions

If any one of the specified untenability conditions occur, then the environment is considered to be untenable for human life. Once the condition is met then if there are any occupants they are trapped or dead. The calculation was done through a set of spreadsheet cells to make sure the calculations were consistent.

Table 4 contains the calculated values for untenability. These results are from the output from FAST modelling.

Fire Growth Rate	Time to Untenability (s)					
	Standard scenario	Short corridor	Layer height only	FED condition only	Ventilation medium	Ventilation high
Slow	350	N/A	N/A	N/A	N/A	N/A
Medium	190	160	150	350	320	360
Fast	110	N/A	N/A	N/A	N/A	N/A

Table 4 Untenability conditions

In modelling the untenability time was normally distributed with a coefficient of variation of 0.3, so the distribution would have a standard deviation of 0.3 multiplied by the mean.

6.4.6. Detection time

Detection times were determined from DETACT- t^2 calculations. DETACT- t^2 uses an unsteady state calculation to determine a detection time for a thermal device. Thermal detection is the only physical model that is readily available and is based on physical effects. Smoke detection is typically done by thermal analogy. The thermal analogy approximates smoke detection for a rapidly growing fire. For the case of a smouldering fire, detection may occur before there is any significant thermal change. This would make the detection time much longer for the thermal analogy, for detection, than what it would be in the real situation.

The usage of the thermal analogy for smoke detection will, in certain cases, yields a building that has a higher probability of fatality in the model. This will occur where there is a fire that goes through a smouldering stage, where the smoke particles would be detected by the smoke detector long before the thermal analogy would predict smoke detector activation. This extended time for smoke detection will increase the probability of fatality to more than what it would actually be. An attempt to compensate for this was by making an assumed smoke detection time in one of the simulations.

The version of DETACT- t^2 used is the one contained inside of FAST 3.1.4. Detection within the modelling was not used, only the DETACT- t^2 component.

Detectors in the building are thermally activated sprinklers. These sprinklers were modelled with an activation temperature of 65°C and a Response Time Index (RTI) value of 100.

Table 5 contains detection times obtained by running DETACT- t^2 on the room of fire origin's dimensions, with a design fire selected.

RTI	Slow (s)	Medium (s)	Fast (s)
100	210	130	72
50	180	110	63

Table 5 Detector activation times calculated from DETACT-t2

Where scenario 5 entails the usage of a smoke detector, the fire is assumed to have been smouldering before the medium fire growth rate occurs. To allow for this, judgement has set the mean time of detector activation to 30 seconds. This assumes that the smouldering has occurred in a period before the time scale of this modelling. In modelling the detector activation time was distributed with a coefficient of variation of 0.3, so the standard deviation would be 0.3 multiplied by the mean value. The normal distribution of detection time is truncated to times between 0 s and 2500 s for the purpose of negative values occurring in detection time, which would not make physical sense.

6.4.7. Occupant movement time

The model currently only covers an individuals probability of fatality, so movement modelling is based upon one occupants movement. Movement time was taken from a stairway velocity data (Pauls 1995). Mean data points were around 1m/s per metre of stair width. A stair width of 1.5m was assumed, although the model's stair width is listed as 2.2m this does not appear to give a realistic value for a single occupant approximation. The extremes of the distribution went from 0.6 m/s per meter of stair width to 1.2 m/s per metre of stair width. Using the stair width of 1.5m the mean becomes 1.5 m/s, the extremes of the distribution become 0.9 m/s and 1.8 m/s respectively.

Based on those data points the extremes are treated as three standard deviations from the mean in a normal distribution. The mean is taken as the mean for that distribution.

This normal distribution was chosen which has a mean of 1.5m/s and a standard deviation of 0.1 m/s.

Normal(1.5 m/s, 0.1 m/s)

The corridor length of 20 meters is used for the total travel distance. The only time the distance is different is where the short corridor has been modelled at 10m. The corridor length is also the travel distance of the occupant.

6.4.8. Occupant response time

The response time was selected from a paper that included a response time distribution to an alarm system (Magnusson 1995) which used a lognormal distribution and has a mean of 130s and a standard deviation of 120s. The response times are all truncated to times between 0 s and 2500 s to stop negative response times from occurring, which do not make sense in the context of these simulations.

LogNormal(130s, 120s)

The paper also included a response time for no alarm system that was taken from expert judgement from the Swedish Fire Service (Magnusson 1995) of:

LogNormal(300s, 300s)

Where a short response time has been used the following distribution has been applied:

Normal (30s, 30s)

Lecture notes from MacLennan (1998) contain a graph of a probability distribution for the time to start movement to exit the building as a weibull distribution. Investigation into this type of response time should be performed.

7. Results

Thirteen scenarios were chosen to test the effect of altering the variables for this model. In each scenario a range of safety factors are examined. The safety factor is a manipulation of the total time for the occupant(s) to escape. For a safety factor of two the occupants escape time is halved. This is for simplicities sake. The actual referenced values are used when the safety factor is equal to one.

Table of Scenarios													
Scenario		1	2	3	4	5	6	7	8	9	10	11	12
Fire Growth	slow		x										
	medium	x			x	x	x	x	x	x	x	x	x
	fast			x									
Corridor Length	short				x								
	long	x	x	x		x		x	x	x	x	x	x
Detector Type	smoke					x							
	thermal	x	x	x	x		x	x	x	x	x	x	x
Response Time	short						x						
	log normal	x	x	x	x	x		x		x	x	x	x
Movement Speed	slow								x				
	medium	x	x	x	x	x	x			x	x	x	x
	fast							x					
Untenability condition	smoke layer									x			
	height												
	thermal	x	x	x	x	x	x	x	x				x
	FED										x		
Ventilation	low	x	x	x	x	x	x	x	x	x	x		
	medium											x	
	high												x

Table 6 Configuration of all scenarios

Each scenario contains a range of safety factors that have been employed in the modelling, as shown in table 6, where a safety factor of one is the unmodified scenario. This probability of failure, where the safety factor is one, is the actual probability of fatality (given that the input values are true distributions). This probability of failure is conditional on the given medium growth fire scenario occurring, with the ventilation conditions as they are in the model and remaining static. Where a different safety factor

has been used the Cumulative Frequency Distribution (CDF) has been translated. This translation mimics the modification of design to allow a higher safety factor in design.

7.1. Scenario 1

Scenario one is the basic scenario that uses a medium fire with the standard compartment dimensions. The human movement times are the standard ones chosen for this modelling. This uses a medium growth rate t^2 design fire.

Safety Factor	Probability of failure
1	0.743
1.2	0.586
1.5	0.409
2	0.222
2.5	0.127

Table 7 Probability of failure for scenario 1 with varying safety factors

7.2. Scenario 2

Scenario two uses a slow design fire. All other variables are maintained from scenario one.

Safety Factor	Probability of failure
1	0.469
1.2	0.321
1.5	0.183
2	0.079
2.5	0.043

Table 8 Probability of failure for scenario 2 with varying safety factors

7.3. Scenario 3

Scenario three uses a fast design fire. All other variables are maintained from scenario one.

Safety Factor	Probability of failure
1	0.880
1.2	0.774
1.5	0.619
2	0.396
2.5	0.273

Table 9 Probability of failure for scenario 3 with varying safety factors

7.4. Scenario 4

Scenario four uses a short corridor length. This modification is made both in the physical fire modelling and in the occupant travel distance.

Safety Factor	Probability of failure
1	0.831
1.2	0.709
1.5	0.533
2	0.307
2.5	0.188

Table 10 Probability of failure for scenario 4 with varying safety factors

7.5. Scenario 5

In this scenario an assumed distribution for a smoke detector was chosen. The smoke detection time has no physical basis. Whereas all the other scenarios are based upon DETACT- t^2 detection times.

Safety Factor	Probability of failure
1	0.344
1.2	0.261
1.5	0.168
2	0.089
2.5	0.053

Table 11 Probability of failure for scenario 5 with varying safety factors

7.6. Scenario 6

In this scenario the short decision time is used. This time is designed to approximate the response times of what fire safety designers use, as an actual response time, rather than using the lognormal response time, which more closely emulates human response times.

Safety Factor	Probability of failure
1	0.418
1.2	0.255
1.5	0.128
2	0.048
2.5	0.022

Table 12 Probability of failure for scenario 6 with varying safety factors

7.7. Scenario 7

Scenario seven uses an altered mean travel velocity of 2 m/s, which is called a fast movement speed in the table of scenarios.

Safety Factor	Probability of failure
1	0.728
1.2	0.581
1.5	0.400
2	0.211
2.5	0.120

Table 13 Probability of failure for scenario 7 with varying safety factors

7.8. Scenario 8

Scenario eight uses a mean movement speed of 1 m/s, which is referred to as a slow travel speed in the table of scenarios.

Safety Factor	Probability of failure
1	0.761
1.2	0.620
1.5	0.423
2	0.229
2.5	0.136

Table 14 Probability of failure for scenario 8 with varying safety factors

7.9. Scenario 9

Scenario nine only uses the layer height condition to trigger untenable conditions. The standard scenario (scenario one) uses three conditions to test untenability.

Safety Factor	Probability of failure
1	0.880
1.2	0.780
1.5	0.607
2	0.372
2.5	0.231

Table 15 Probability of failure for scenario 9 with varying safety factors

7.10. Scenario 10

Scenario ten only uses Fractional Equivalent Dose (FED) to determine untenability.

Safety Factor	Probability of failure
1	0.257
1.2	0.177
1.5	0.099
2	0.043
2.5	0.022

Table 16 Probability of failure for scenario 10 with varying safety factors

7.11. Scenario 11

Scenario eleven has the same configuration as scenario one except that the ventilation in the corridor to the outside is triple in width. This triples the corridor's external ventilation.

Safety Factor	Probability of failure
1	0.330
1.2	0.218
1.5	0.125
2	0.056
2.5	0.030

Table 17 Probability of failure for scenario 11 with varying safety factors

7.12. Scenario 12

Scenario twelve uses increased ventilation like scenario eleven. Except that the ventilation from the corridor to the outside is increased by five times from the corridor ventilation of scenario one.

Safety Factor	Probability of failure
1	0.256
1.2	0.166
1.5	0.090
2	0.039
2.5	0.021

Table 18 Probability of failure for scenario 12 with varying safety factors

7.13. Summary

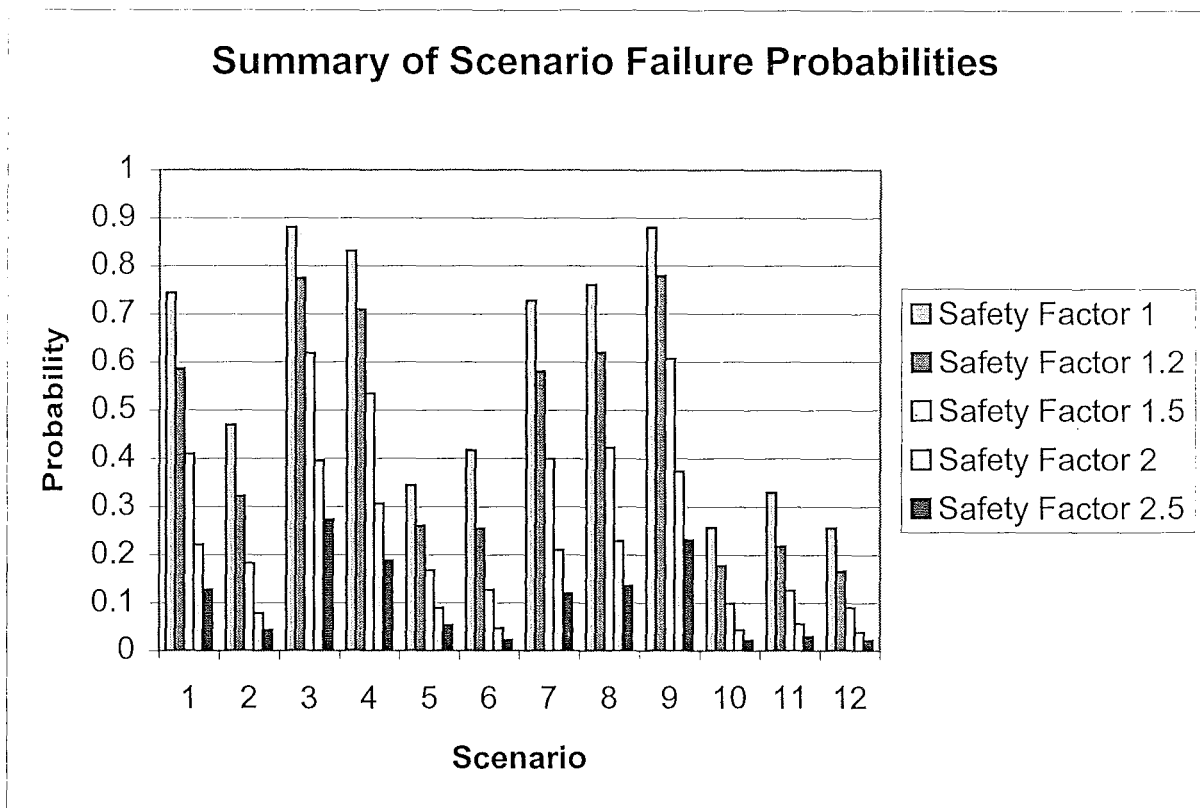


Figure 9 Summary of all modelling results

The results in figure 9 can only be compared in a relative manner. An event tree of the possible scenarios has to be evaluated to compare these results by individual risk. In this modelling the benchmark for comparison is the standard design scenario one. The effects studied are for a safety factor of one. All the other results are a translation of this result, which is designed to be the real situation, so their effect is dependant on the shape and distribution of the time available after egress distribution.

The scenarios that are worse, in a relative comparison with scenario one, are scenarios 3, 4, 8 and 9. Scenario three has a fast fire growth, this growth is expected to cause higher likelihood of fatality if it is not controlled. Scenario four has a short corridor length. The shorter corridor, 10 metres instead of 20 metres, will halve the volume of the corridor. The occupant travels half the distance of scenario one, but it appears that the halving of corridor volume has a larger effect upon probability of fatality than shortening movement

distance. Scenario eight has a slower occupant movement speed, the mean speed being 1 m/s compared with 1.5 m/s in scenario one. This does not appear to have much effect as also shown in scenario four with the shorter movement distance. Scenario nine has a similar probability of failure compared with scenario three, where the design was a fast t^2 fire, though the only change made was using only smoke layer height as an untenability condition. This rapid untenability condition has probably come from the effect of having only a low level of ventilation in the compartments modelled.

The only scenario that has a result similar to the standard scenario one is scenario seven. In scenario seven a fast movement speed, with a mean of 2 m/s, was used. This marginal improvement of increasing the movement speed supports the minor effect of slowing the movement speed in scenario eight, and the marginal effect in scenario four.

Scenarios 2, 5, 6, 10, 11 and 12 all give a very significant increase in the level of safety determined by Monte Carlo simulation. The effect is more significant than in the previously discussed scenarios. This may just be an effect of where the data has been sampled from the time available after egress distribution, which requires further examination of the distributions. Scenario two makes use of a slow t^2 design fire, and as expected the effect is a reduction in the probability of failure. Scenario five uses a smoke detector, the detector is an assumption with a large standard deviation, but this gives the expected result of reducing the probability of fatality. Scenario six is a reduction of the human response time, where the decision to exit the building after hearing the alarm is reduced, which gives the expected result of reducing the likelihood of fatality. Scenario ten uses a fractional equivalent dose of 0.25 as the untenability condition, compared with convective heat triggering untenability in the vast majority of cases. This is not necessarily expected but it suggests that in most of the results here that the fire environment is insufficiently ventilated. The FED of 0.25 is not typically used by designers either 0.5 or 1.0 are used that would give a slightly improved safety level to a building. Scenarios eleven and twelve both have increased levels of ventilation to the outside. The effect of this is (as expected) a much lower probability of fatality, in scenario twelve the convective heat untenability condition was not triggered first.

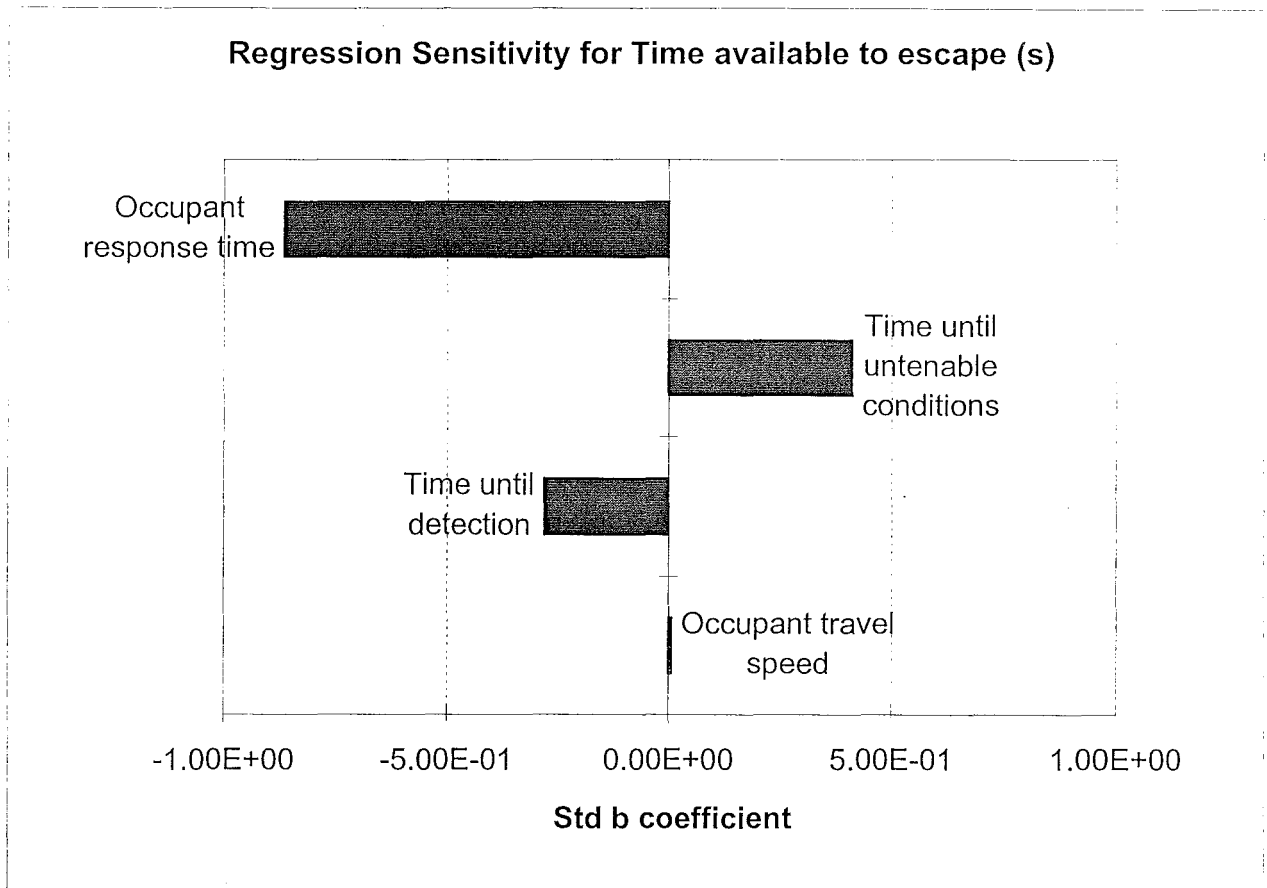


Figure 10 Regression Sensitivity for the Effect of Modelling Inputs on Time Available to Escape

In figure 10, the most influential input for the model is occupant response time. Occupant response time has an R^2 value of -0.86, which means that it correlates very strongly with reducing the time available to escape as occupant response time increases. Time until untenable conditions correlates positively to increasing the time available to escape with $R^2 = 0.41$. This is as expected, although the contribution from the distribution may be different with refinements in modelling, the distribution of untenability is partially to deal with the unpredictability of the fire scenario and the variation in CFAST/FAST modelling results. The occupant travel speed correlates with $R^2 = 0.007$. This correlation is so insignificant in influence that in future modelling should be treated as a deterministic value. What that value should be requires further investigation.

When examining the safety factors the mean time available after egress was not zero. This is unavoidable when actual response distributions have been chosen. The safety factor was just a modification of the total time taken to escape from the building. The scenario that was closest to zero was scenario 2. This scenario had a slow t^2 fire growth, with the appropriate detection time calculated by DETACT- t^2 . The mean time available to escape was -2.5s. This is close enough to zero to examine the actual effect of an egress design. The equivalent for a medium fire is scenario one with a safety factor of 1.5, the mean time available after egress is 8s. This gives a probability of failure of 0.41. The probability of failure is lower than scenario two because of the more rapid response of a heat detector in a medium fire growth compared with a slow fire growth.

When the safety factor is one the probability of failure is 0.469. Applying the standard safety factor of 2 (FEDG 1994) the probability drops to 0.079. When the safety factor is 2.5 the probability of failure is 0.043, which is almost half of the safety factor of 2. In contrast to these results, where the results give a low probability of failure (where these would be extremely low values when placed into an event tree of all scenarios). It is not unusual for designer to alter safety factors, in the survey results one designer decides if using a safety factor is appropriate and others do not use safety factors over the total time to escape the building. This can sometimes mean using a lower value for safety factor. When changing to a safety factor of 1.5 the probability of failure becomes 0.183. When shifting to a safety factor of 1.2 the probability of failure becomes 0.321, which is approximately three-quarters of the probability of a safety factor of one.

The values used for scenario two are values that are averages. Designers use what are claimed to be extreme values. Typically, the time used with a safety factor of two is around 2 minutes at the maximum for an office, from the survey results. In the slow fire growth scenario these times are longer, including the extended detection time. This adds up to 7 minutes before the safety factor is applied.

8. Survey

8.1. *Survey objective*

This survey is for the SFPE Task Group on the Standardisation of Performance Based Design Criteria. The results will be published along the data collected from the United States. The intention of the questions is to determine what design values are being used by practicing fire safety engineers. This information is compared with the results of the modelling.

8.2. *Timed egress survey questions*

- 1) What country are you based in?
- 2) What region are you based in?
- 3) How many projects a year involve building designs which include timed egress fire hazard analysis?
- 4) What criteria do you use for tenability (e.g. CO, CO₂, O₂, HCN, visibility, radiation from upper layer, temperature of lower layer, etc.)? Please list all criteria and provide references if applicable. If the criteria varies depending upon the building occupancy please indicate the specific occupancies (e.g. business, residential, educational, etc.) and the corresponding travel speed(s).
- 5) What occupant travel speed(s) do you use? If the speed varies depending upon the building occupancy please indicate the specific occupancies (e.g. business, residential, educational, etc.) and the corresponding travel speed(s).
- 6) What occupant response time(s) do you use? If the time varies depending upon the building occupancy please indicate the specific occupancies (e.g. business, residential, educational, etc.) and the corresponding response time(s).
- 7) What factors of safety do you employ and how do you use them? If the factors vary depending upon the building occupancy please indicate the specific occupancies (e.g. business, residential, educational, etc.) and the corresponding factor(s) of safety.
- 8) What computer programs do you use to estimate fire growth and development and/or time to untenable conditions?

- 9) Do you have a standard design fire? If so, what is it? If the design fire varies depending upon the building occupancy please indicate the specific occupancies (e.g. business, residential, educational, etc.) and the corresponding design fire.
- 10) Is the above information standardised within your organisation?

8.3. Results

1) What country are you based in? Responses

New Zealand	8
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2) What region are you based in? Responses

Auckland	4
Christchurch	3
Wellington	1

3) How many projects per year? Responses (approximate)

0-40	6
41-80	1
81-120	1

4) What criteria used for Responses untenability?

Layer Height 1.5m	6 /7
Convective heat 65C	3 /7
Radiation from upper layer 200C (or 2.5kW/m ²)	5 /7
Fractional Equivalent Dose (FED)	1 /7
Not stated	1 /1

**5) What occupant travel speed(s) Responses
do you use?**

0-59 m/min	2 /8
60-69 m/min	6 /8
70-79 m/min	8 /8
80+ m/min	0 /8

**6) What occupant response times do you Responses
use?**

Office	0-30s	2
	31-60s	2
	61-120s	3
	121-180s	1
Residential or sleeping occupancy	120-240	2
	241-360s	2
	361-480s	2
	Not stated	2
Retail	90-150	1
	Not stated	7

**7) What safety factor do you Responses
employ?**

2	6
3	1
Not stated	1

**8) What computer programs do Responses
you use?**

Branz Fire	2 /8
CFAST/FASTLite	8 /8
Evacnet+	1 /8

Firecalc	4 /8
Firesys	1 /8
Fire Simulator	1 /8
First	1 /8
FPE Tool	5 /8

9) What is your standard design fire?		Responses
Office	medium t^2	3
	fast t^2	2
	ultra fast t^2	0
Residential	medium t^2	2
	fast t^2	3
	ultra fast t^2	1
usage of t^2 fire growth		8 /8
heat release curves (furniture or materials)		1 /8

10) Is this information standardised in your organisation?

Yes	6
No	2

8.4. Discussion of Results

All the designers that answered the survey were based in New Zealand.

The designers were spread amongst Auckland, Wellington and Christchurch.

Projects completed per year were mostly in the under 40 projects category.

The conditions to determine untenability is mostly layer height and radiation from the upper hot layer. Three of seven respondents use convective heat as the terminating condition for untenability.

The movement speed range that is most commonly used is 60-79 m/min. The maximum of these results was ~76 m/min, so the actual range is 60-76 m/min.

There is a significant spread of occupant response times for both office and residential buildings. It is apparent that there is no generally accepted response times for humans. The ranges presented in the survey results for occupant response times are the sum of all factors used by a designer. This includes investigation time, decision making time, and any other pre-movement activities.

Six of eight designers use a safety factor of two, one of eight uses a safety factor of three under certain conditions. There is a level of variation of what the safety factor is applied to. There is also a variation on where the safety factor is to be used, in some cases whether it is used at all. In some cases the safety factor is not used on the movement time of the occupant.

The program that all designers had was CFAST/FAST/FASTLite. This program is also the program chosen for physical fire modelling for this project.

It appears that a design fire, which is medium or fast for t^2 fire growth, is typical in design. This depends upon the fire scenario being evaluated. All respondents used a t^2 fire growth in design, depending upon the occupancies or stored materials in the building.

In six of the eight organisations, their design approach is standardised.

The vast majority of designers are using a safety factor of two. Which is recommended by this report.

9. Conclusions

9.1. Discussion

The three most influential factors, for this modelling, in influencing the probability of failure of design are the following inputs:

- Occupant response time
- Time until untenable conditions
- Time until detection

The input that is deterministic is:

- Occupant travel speed

Altering safety factors makes significant changes to the probability of egress failing. These changes can be very dangerous for life safety.

Both the limits imposed on the model and the inputs for the model determine the probability of failure.

The time taken for activities after alarm sounding, but before movement to leave the building, appear to be underestimated in deterministic design calculations. The safety factor of two appears to compensate for underestimated time values for human activities. From the sensitivity analysis, it appears that the occupant movement speed is insignificant when compared with the time to untenability, occupant response time, and the time taken until the fire is detected.

9.2. Recommendations

Designers should not alter safety factors and other accepted inputs or input distributions in calculations without justifying with experimental data and having an understanding of the systems involved in human egress. Changes without this understanding is likely to cause life safety to be reduced.

Safety factors in their current form (the survey in chapter eight, and the Fire Engineering Design Guide (1994)) should not be reduced until further research is performed into the effects on life safety have been more thoroughly examined. The majority of designers use of safety factor of two (75% of those surveyed), which is recommended by this report.

The conditional probability for the: given design fire, heat detectors, and no fire suppression by sprinklers, gives a conditional probability of failure between 5% and 40% for a safety factor of two. Compared with a safety factor of 1.5 which gives a conditional probability of failure between 10% and 60%. A safety factor of one which gives a conditional probability of failure between 25% and 90%.

10. Future Work

- Finding the decision making time for New Zealand occupant groups, and the type of distribution more accurately models this time.
- Reduction of the knowledge uncertainty about human decision making time.
- Physical fire modelling needs further refinement for determination of untenability times.
- To complete an event tree of the scenarios, and their probability of occurrence. This would allow the calculation of the life safety of an individual in a given building.
- Development of a standard of acceptable risk to life safety, for an individual in a given building for the time spent in the building.
- Determining a method for simulating a multiple occupant egress. This would determine the number of fatalities in a given scenario. This information would allow a FN-curve for a building to be calculated.
- Development of a standard for which the FN-curve would be compared to determine whether the risk to life safety is acceptable. In terms of risk, and societies perception of risk.
- The values used are not values from New Zealand data. Cultural differences and differing occupant groups are likely to give different distributions for modelling inputs. Therefore, New Zealand data should be collected to improve the accuracy of the probability of failure for New Zealand building design.

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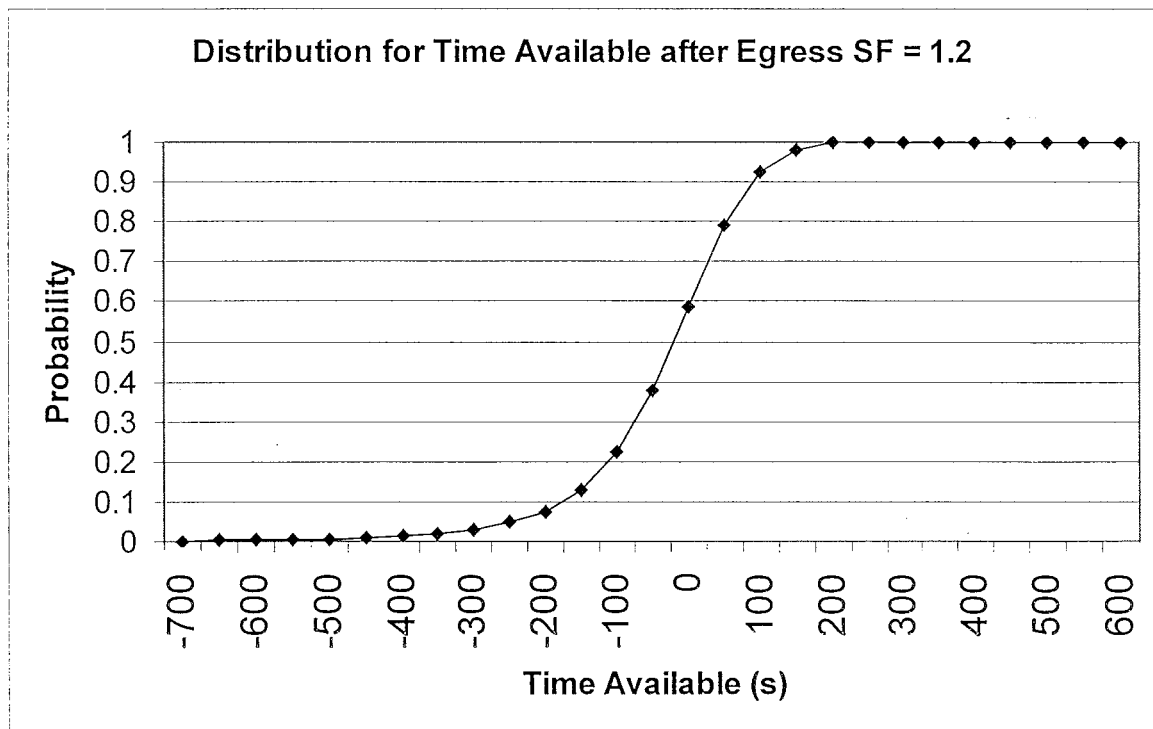
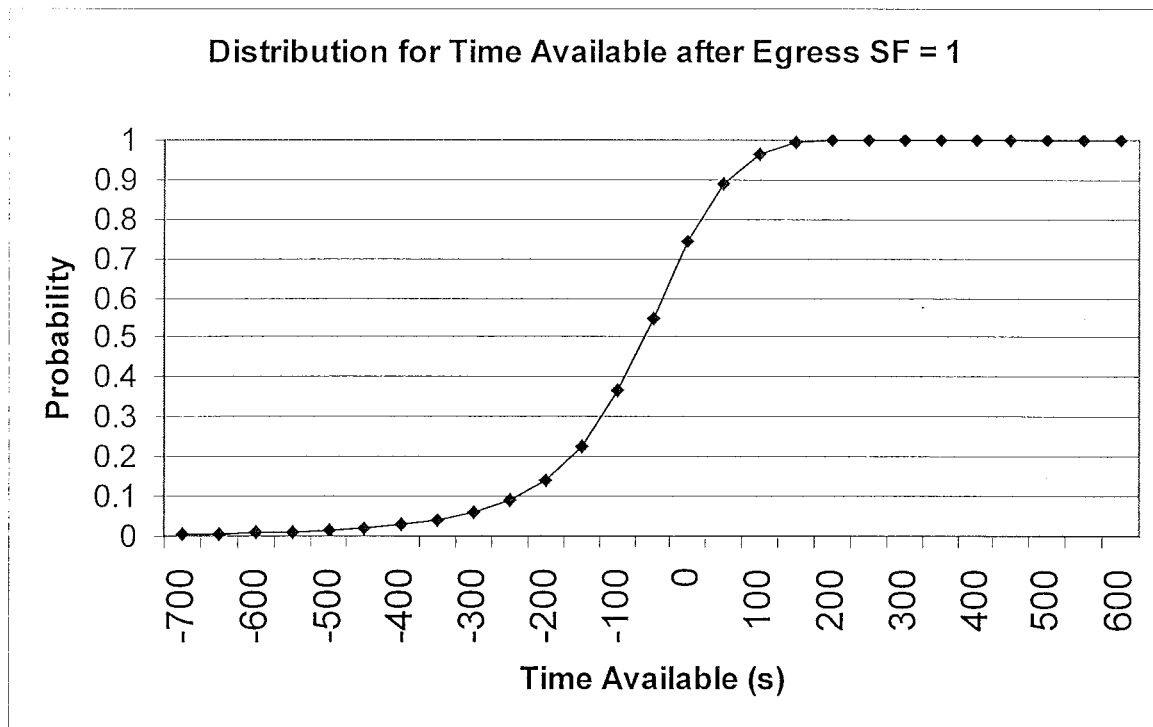
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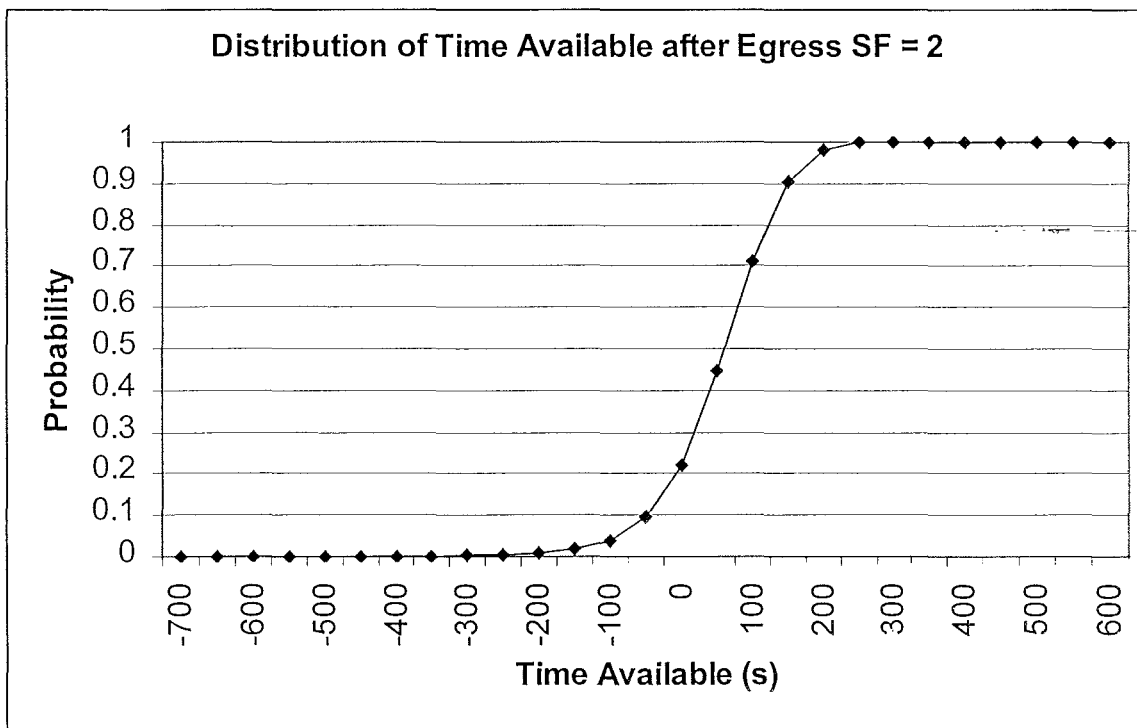
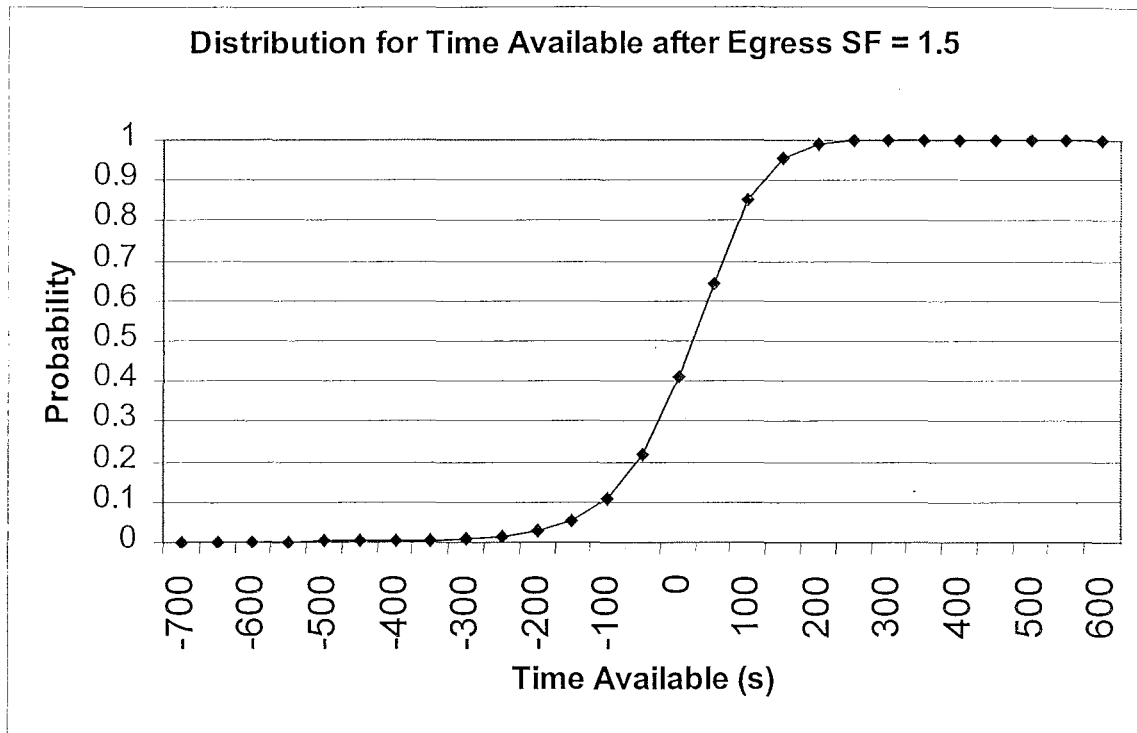
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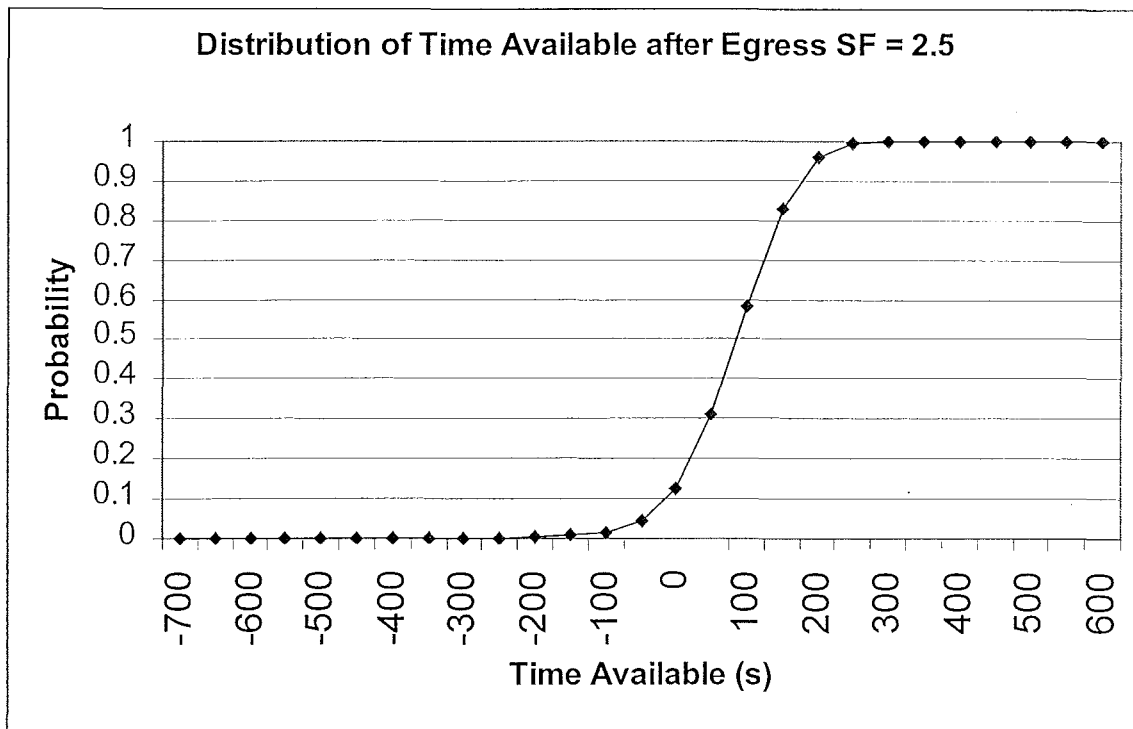
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Appendix A

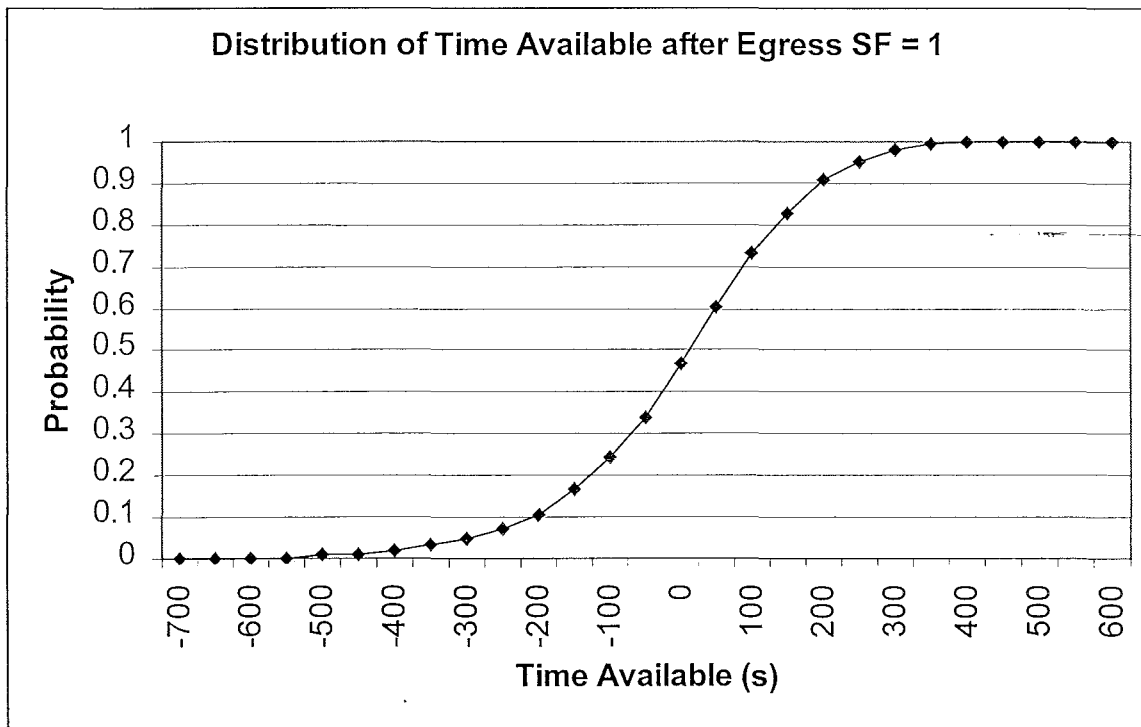
Scenario 1 – Standard configuration

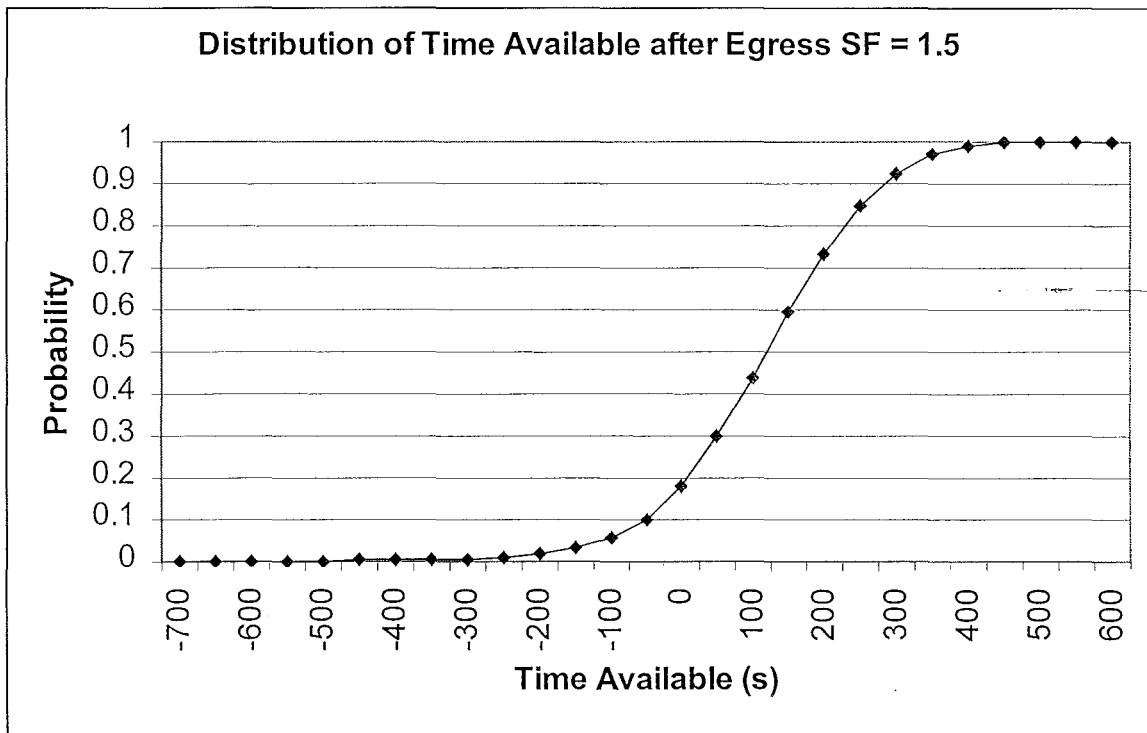
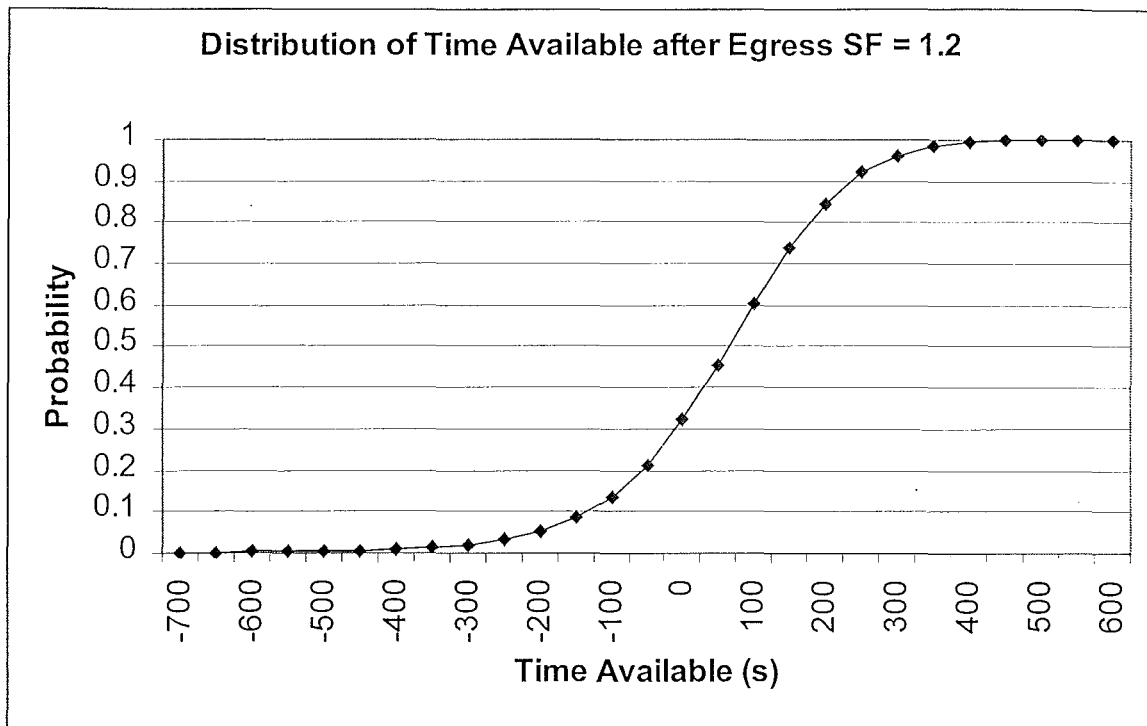




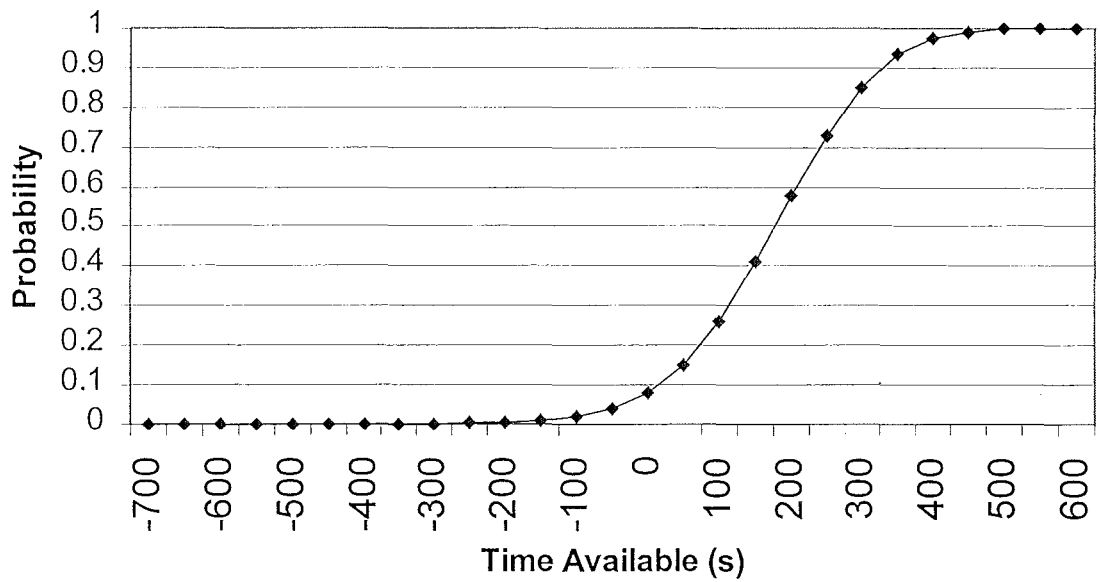


Scenario 2 – Slow t^2 fire growth

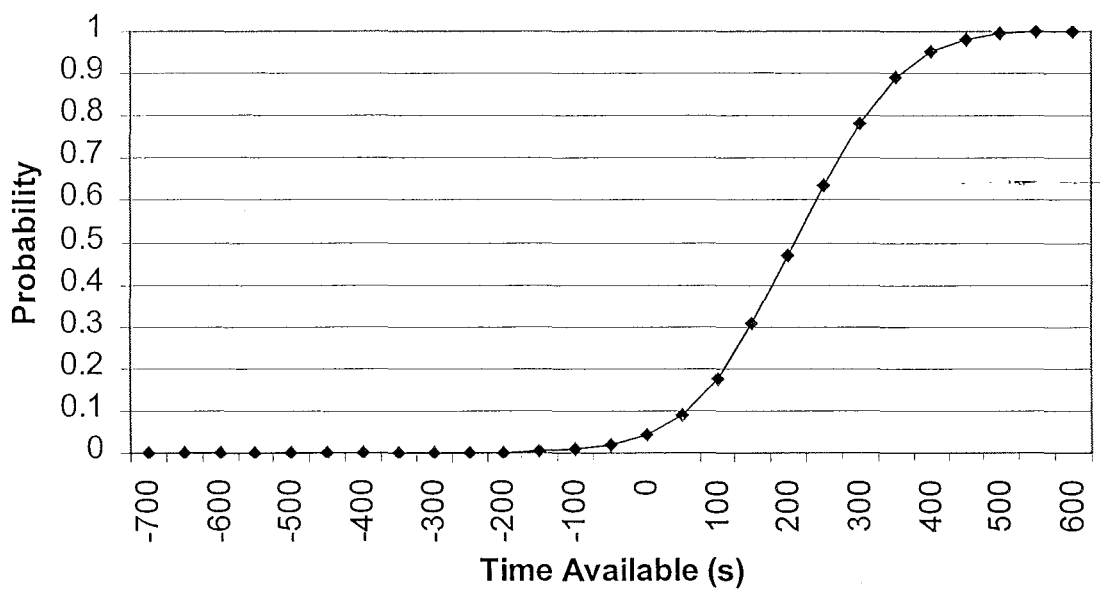




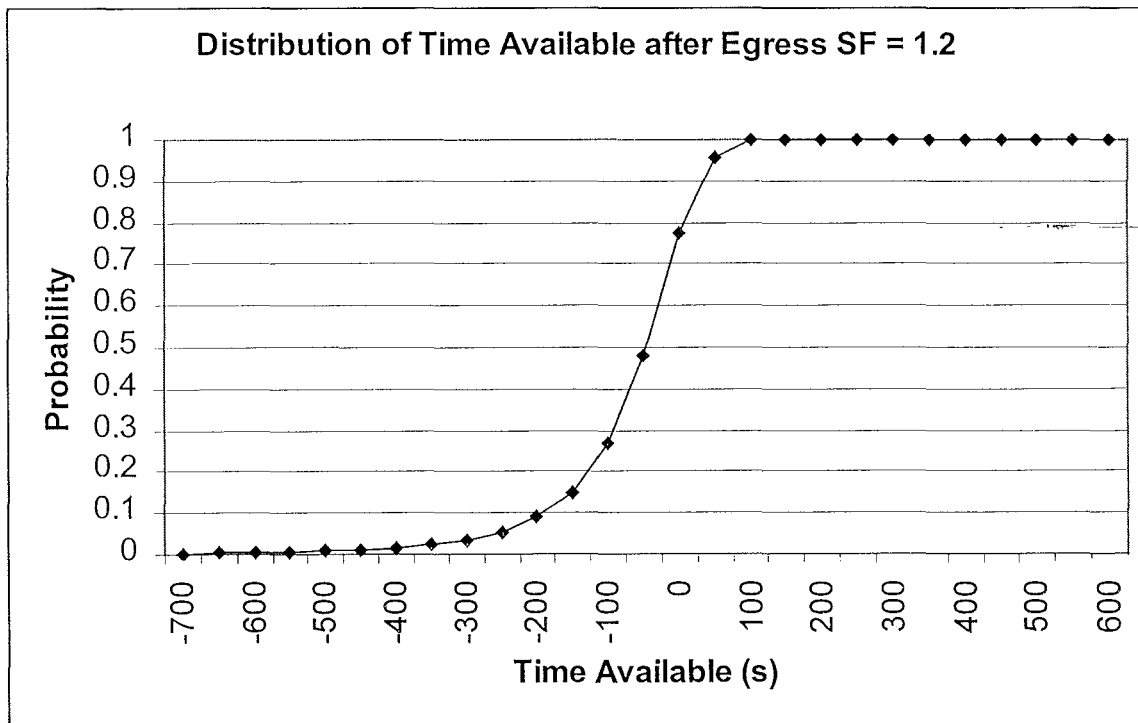
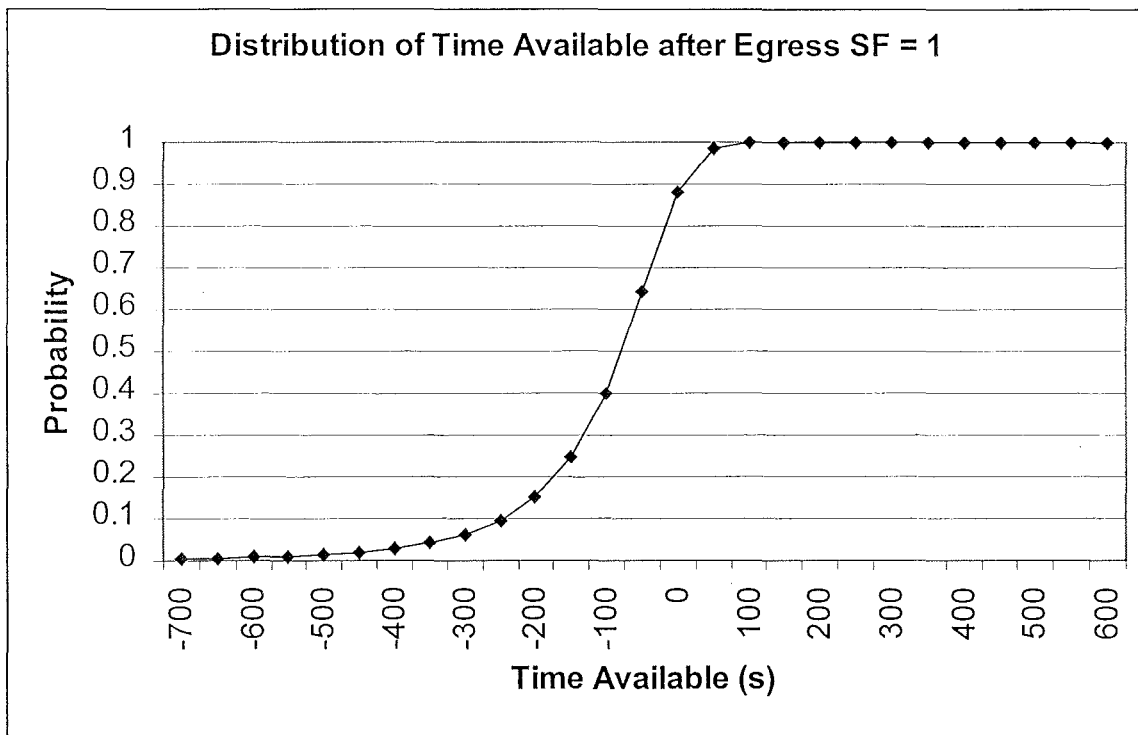
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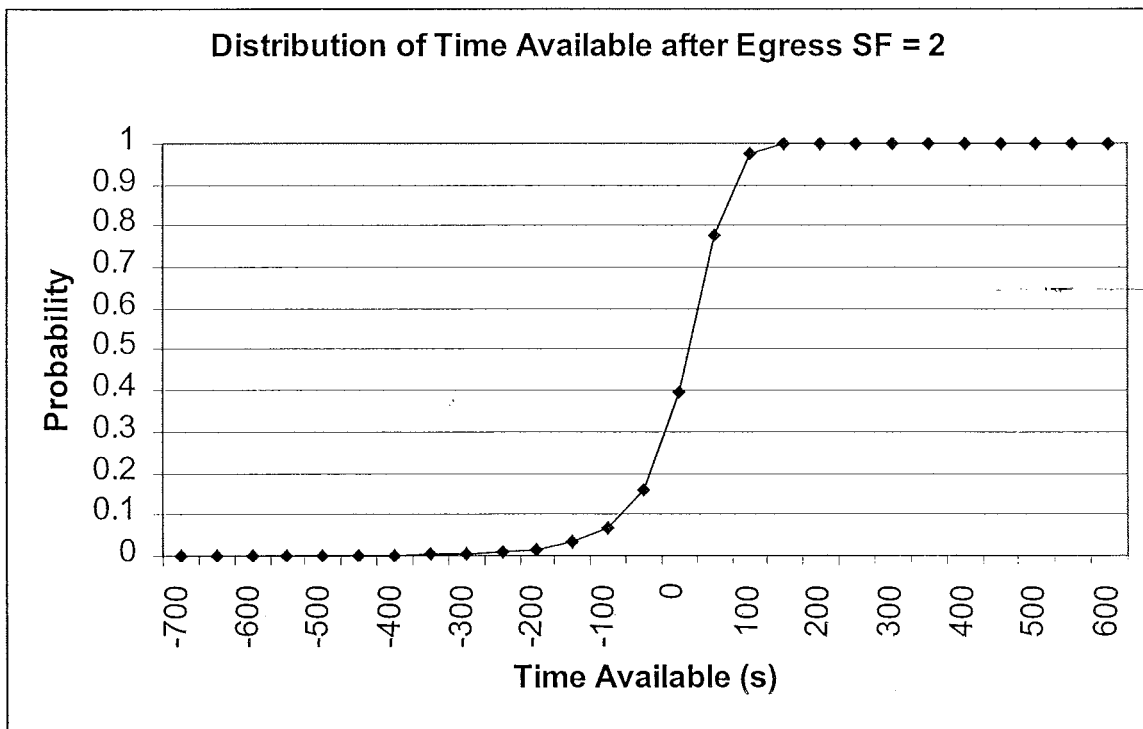
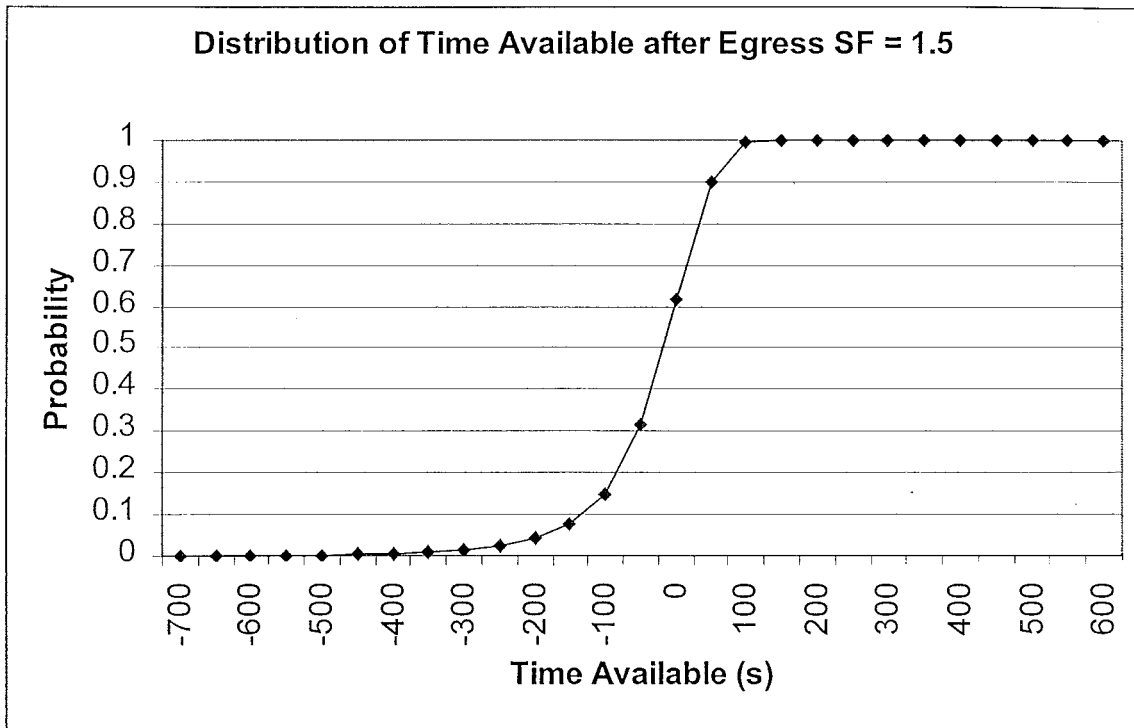


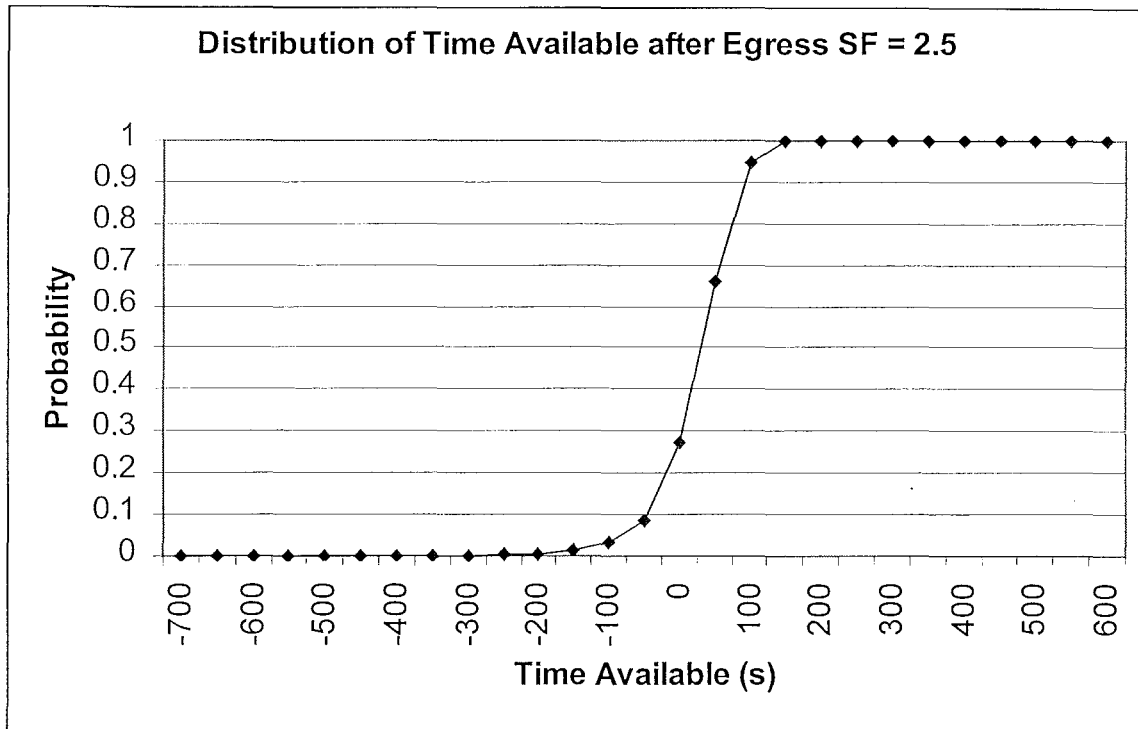
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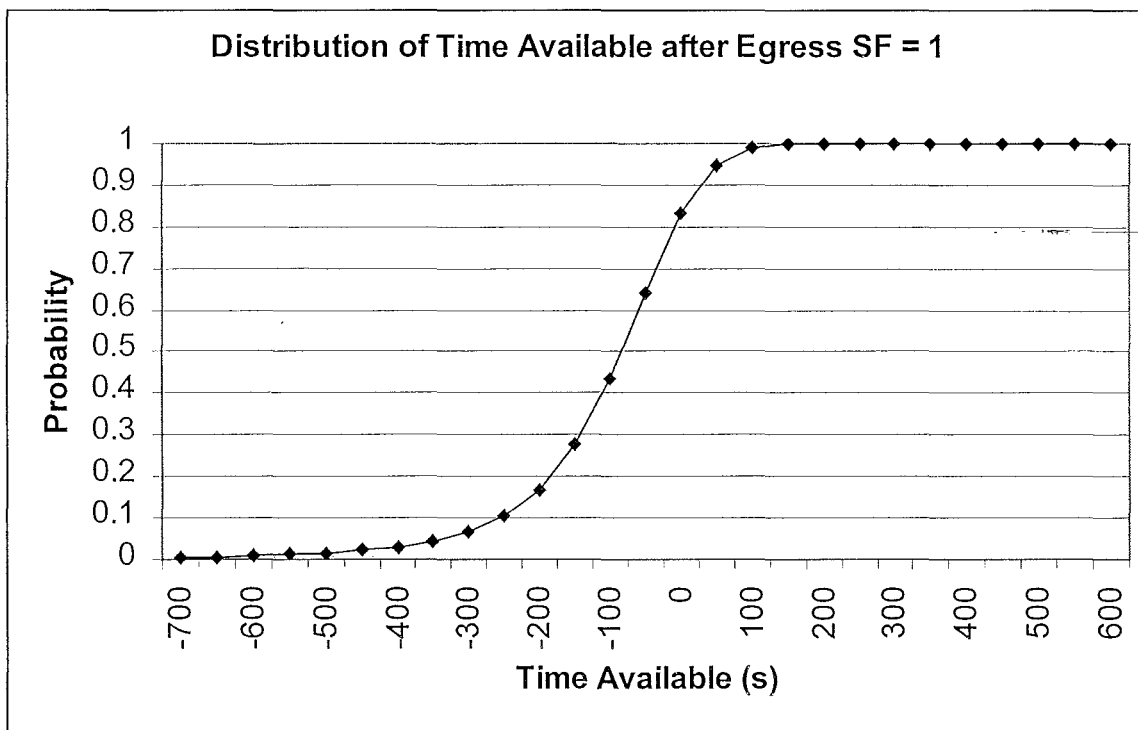
Scenario 3 – Fast t^2 fire growth

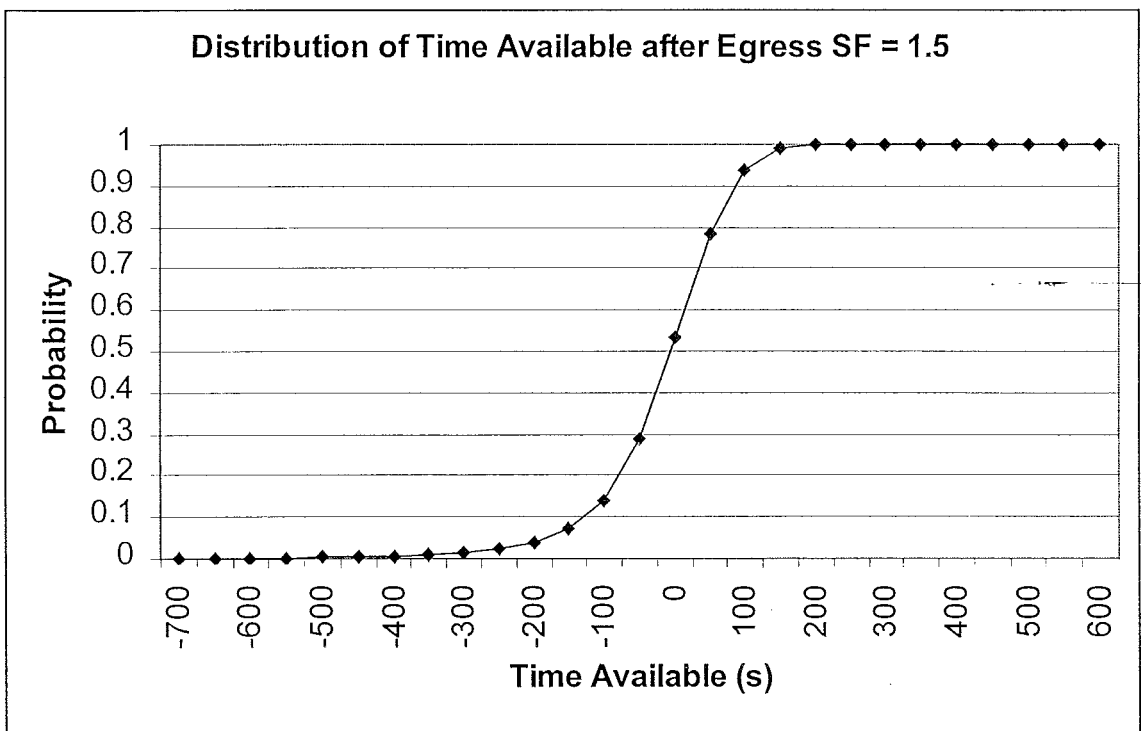
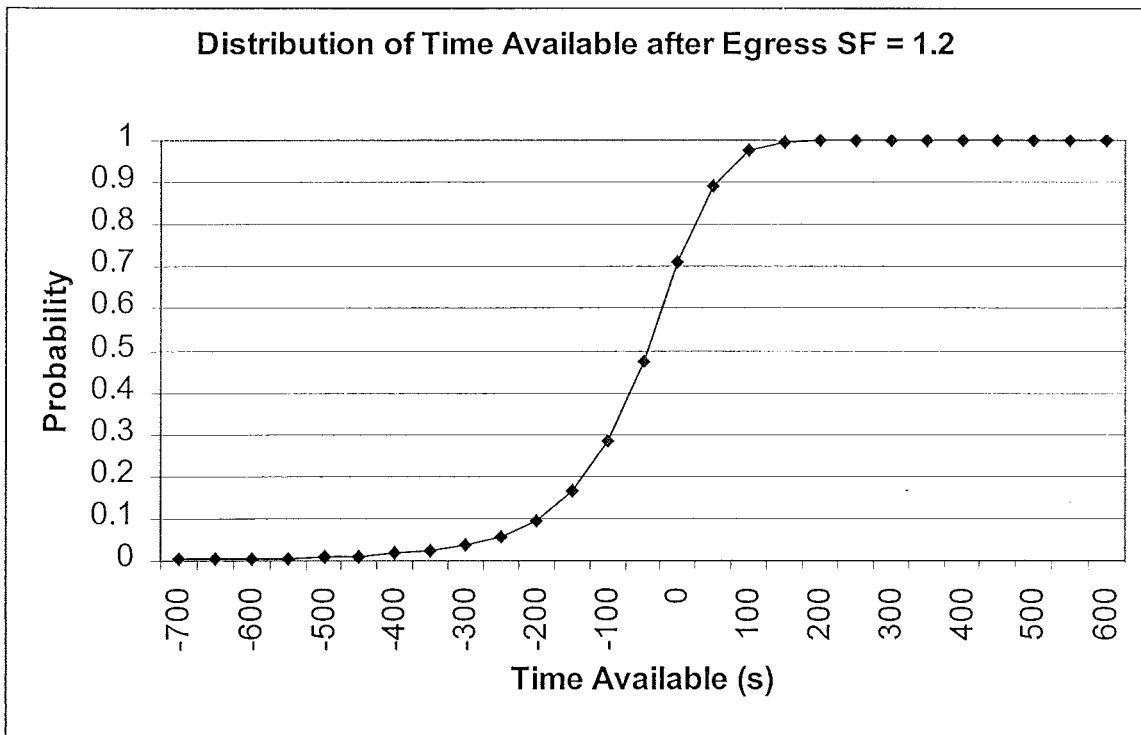


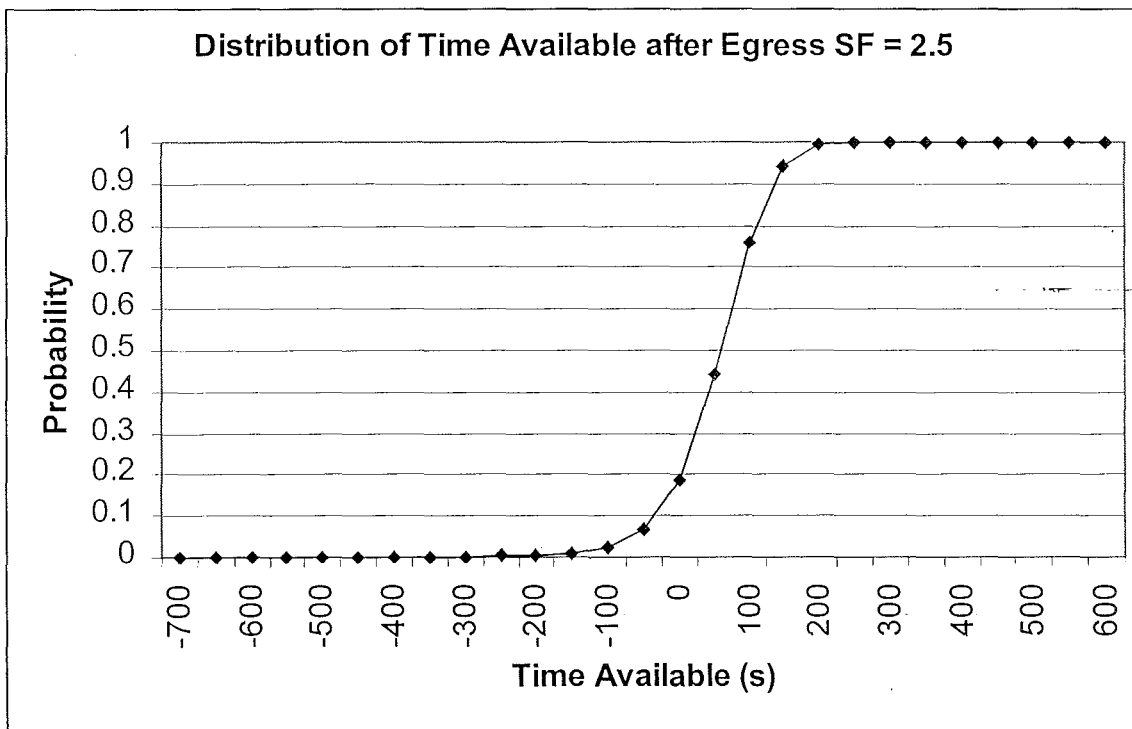
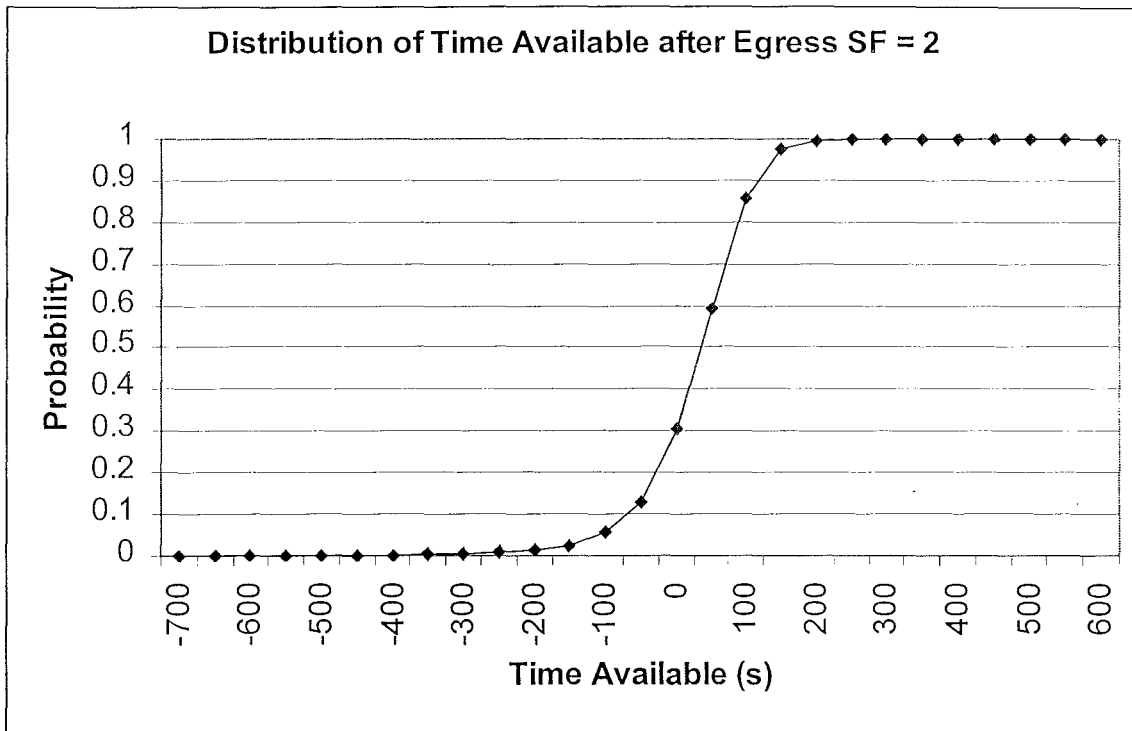




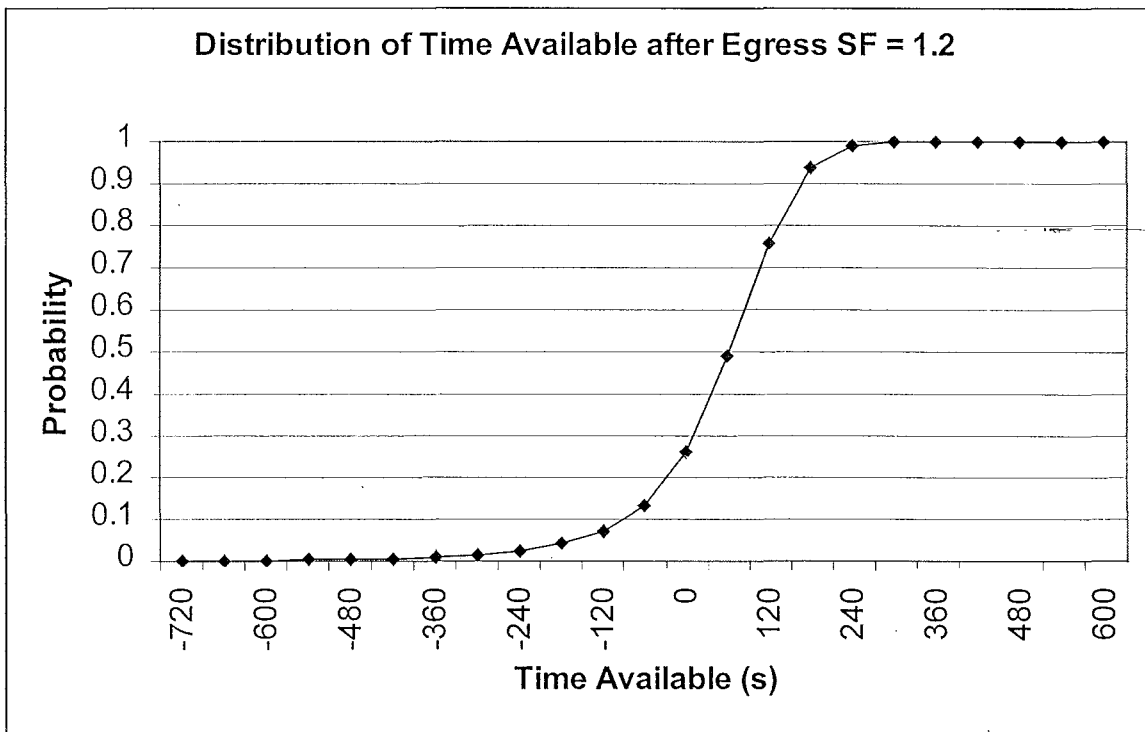
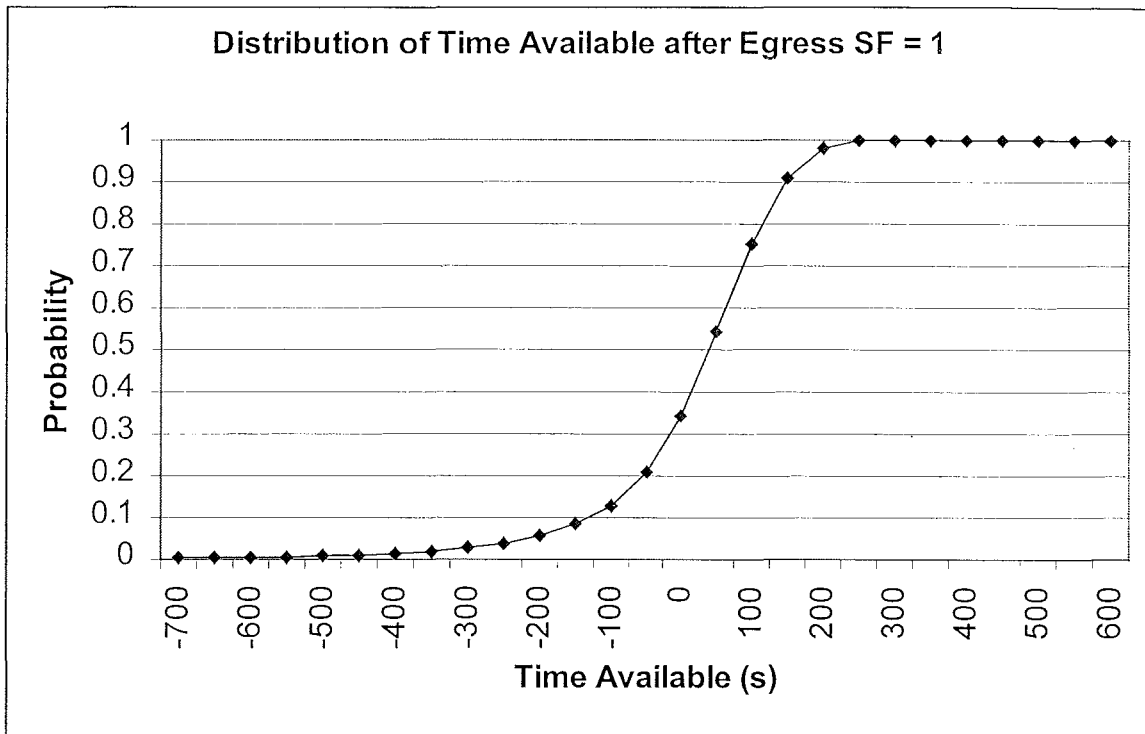
Scenario 4 – Short corridor length

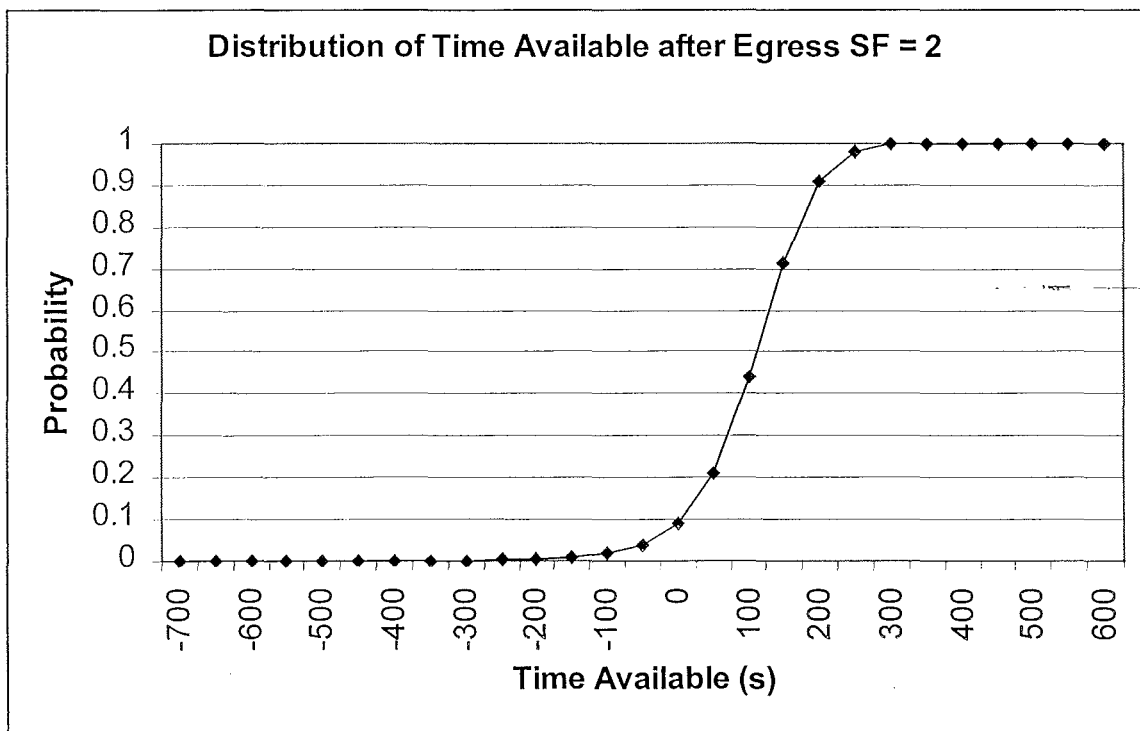
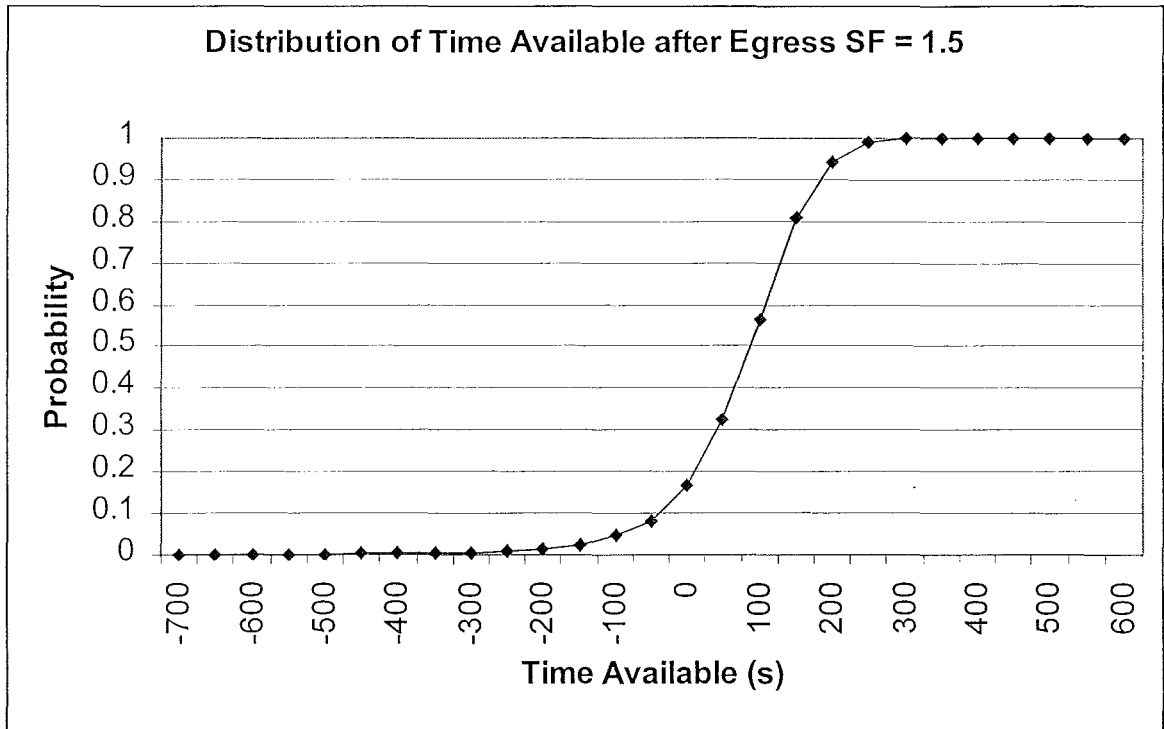


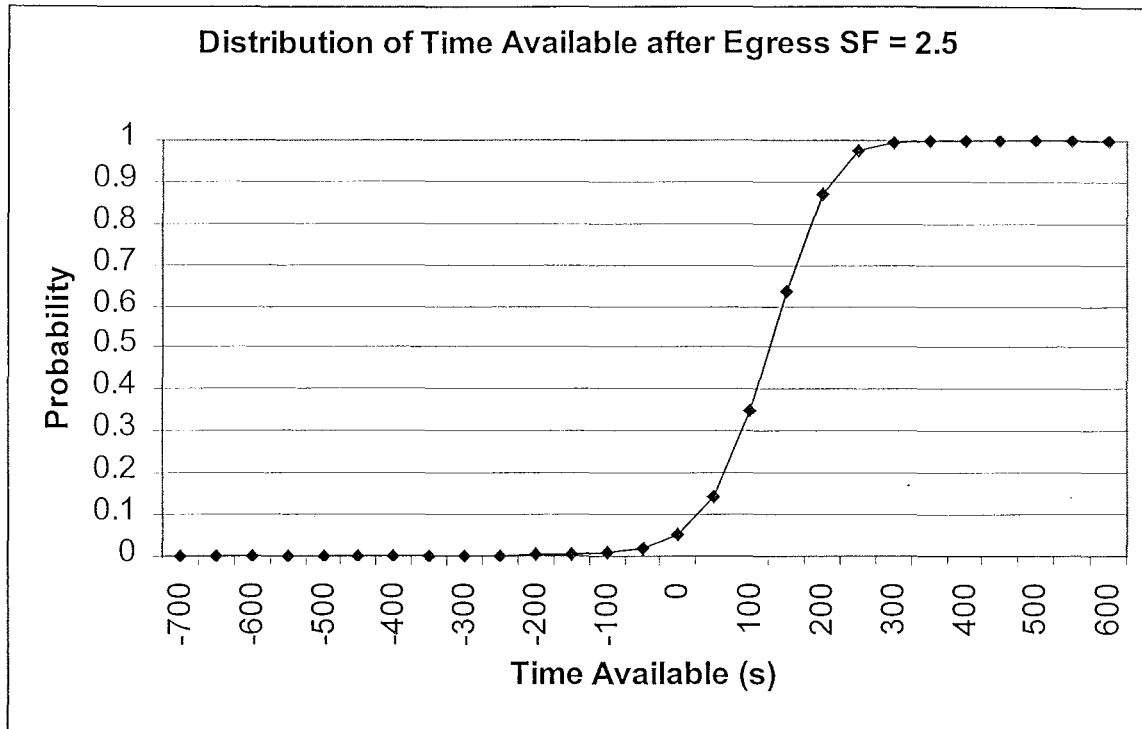




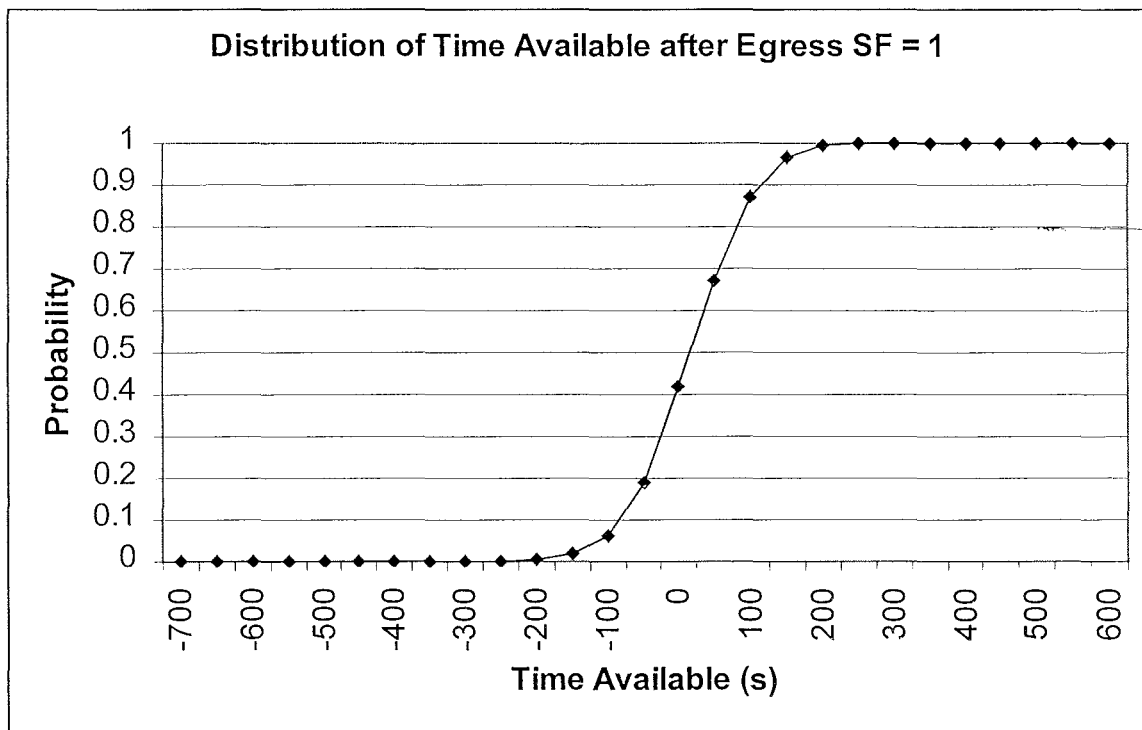
Scenario 5 – Smoke detection

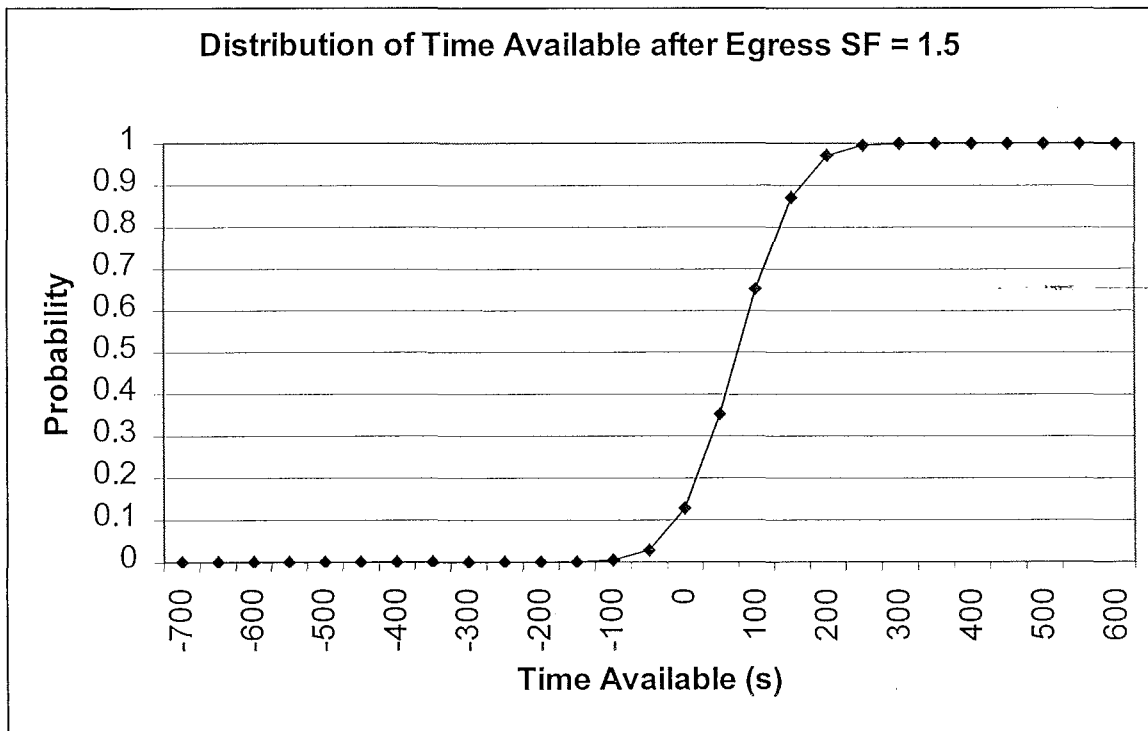
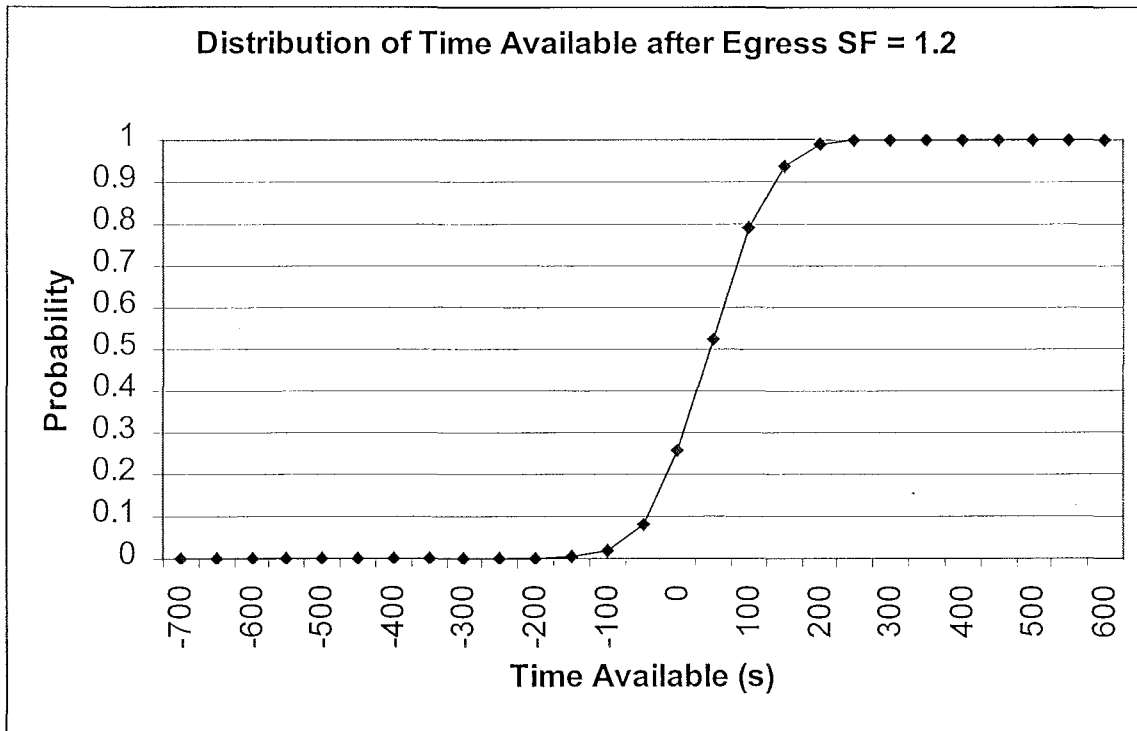


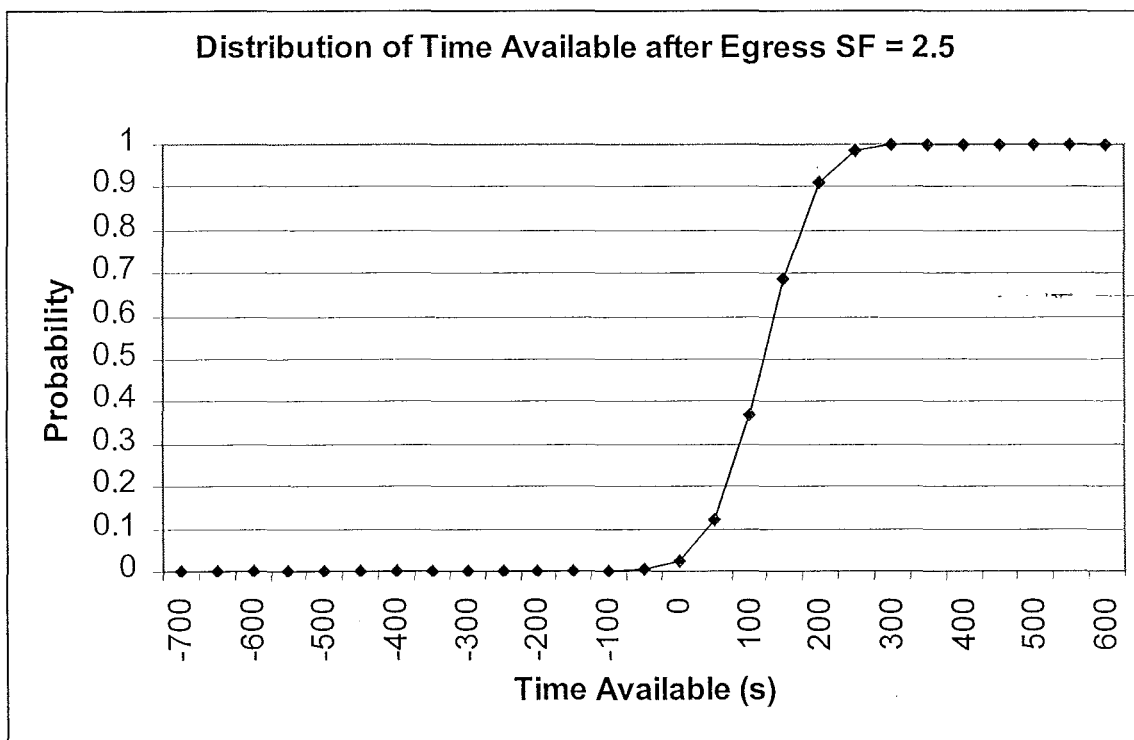
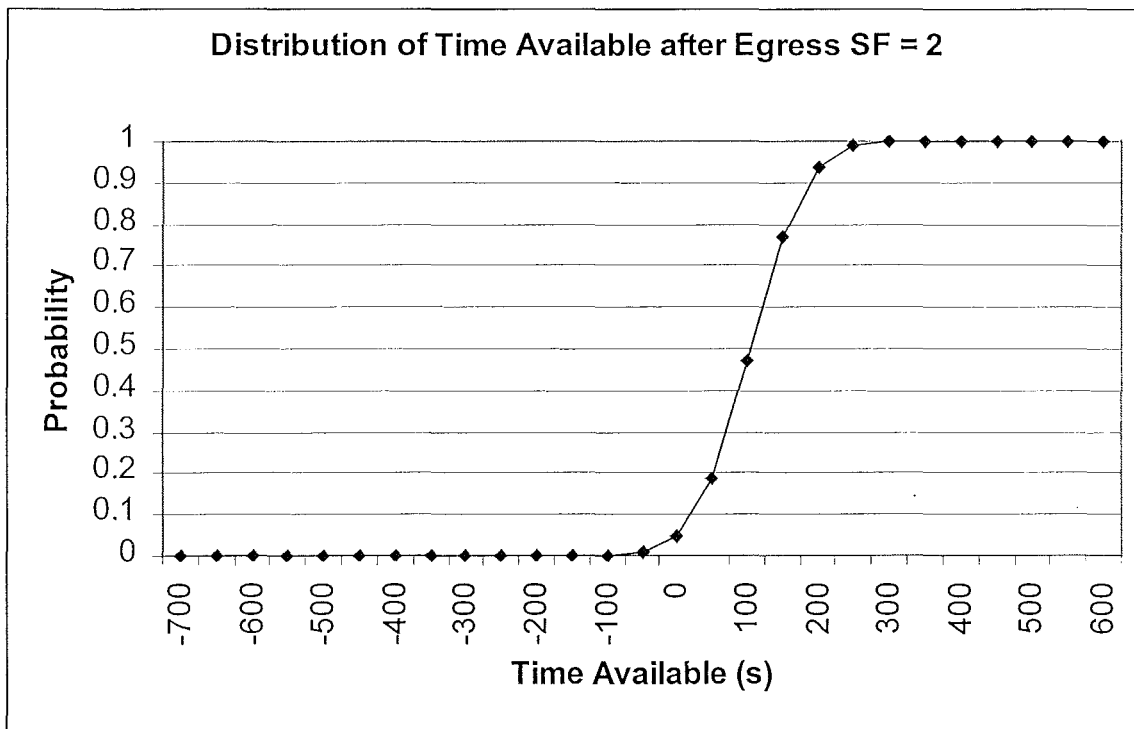




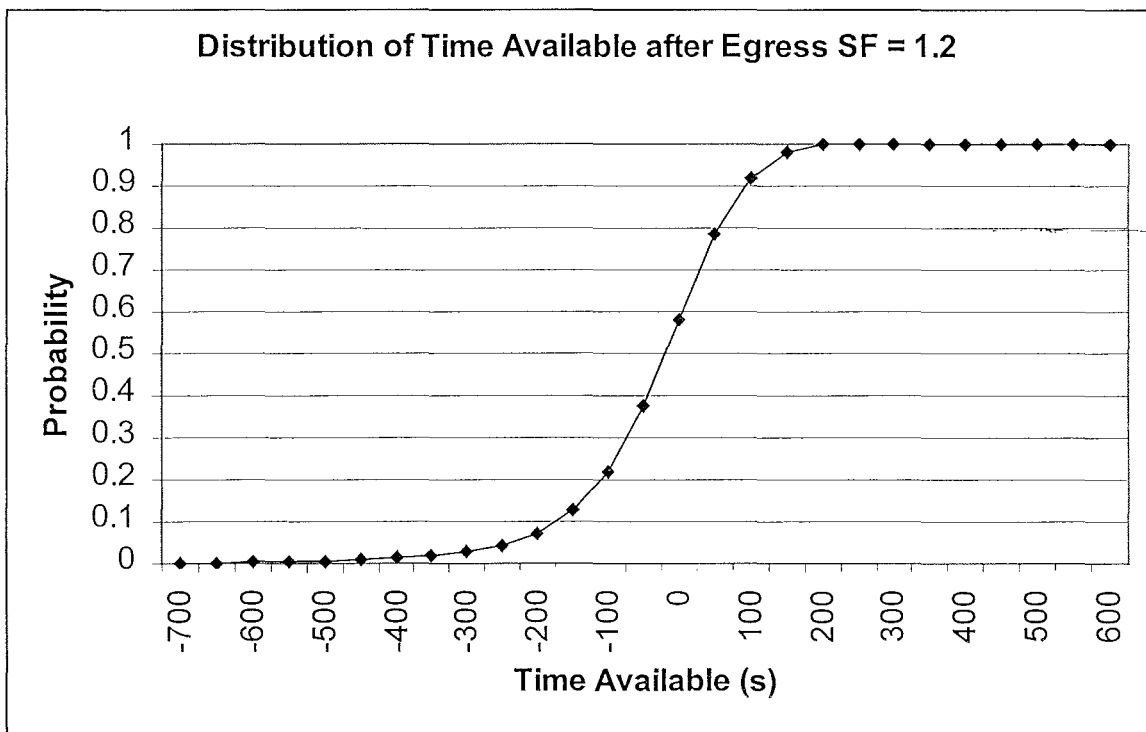
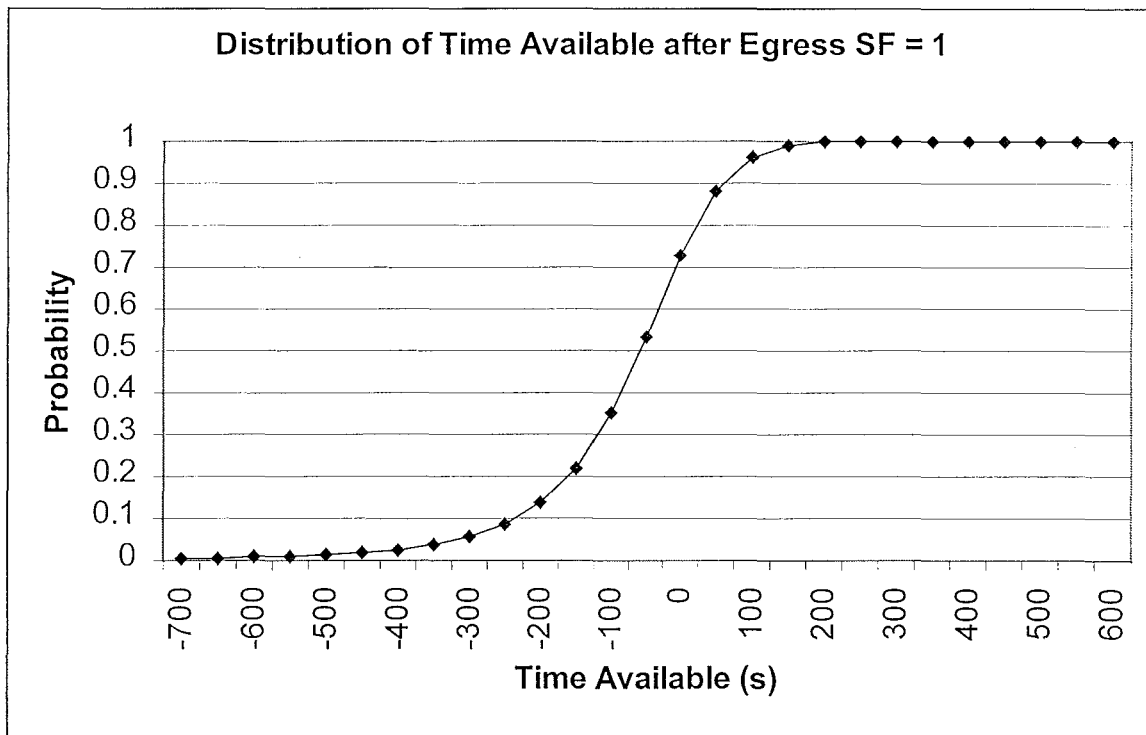
Scenario 6 – Short human response time

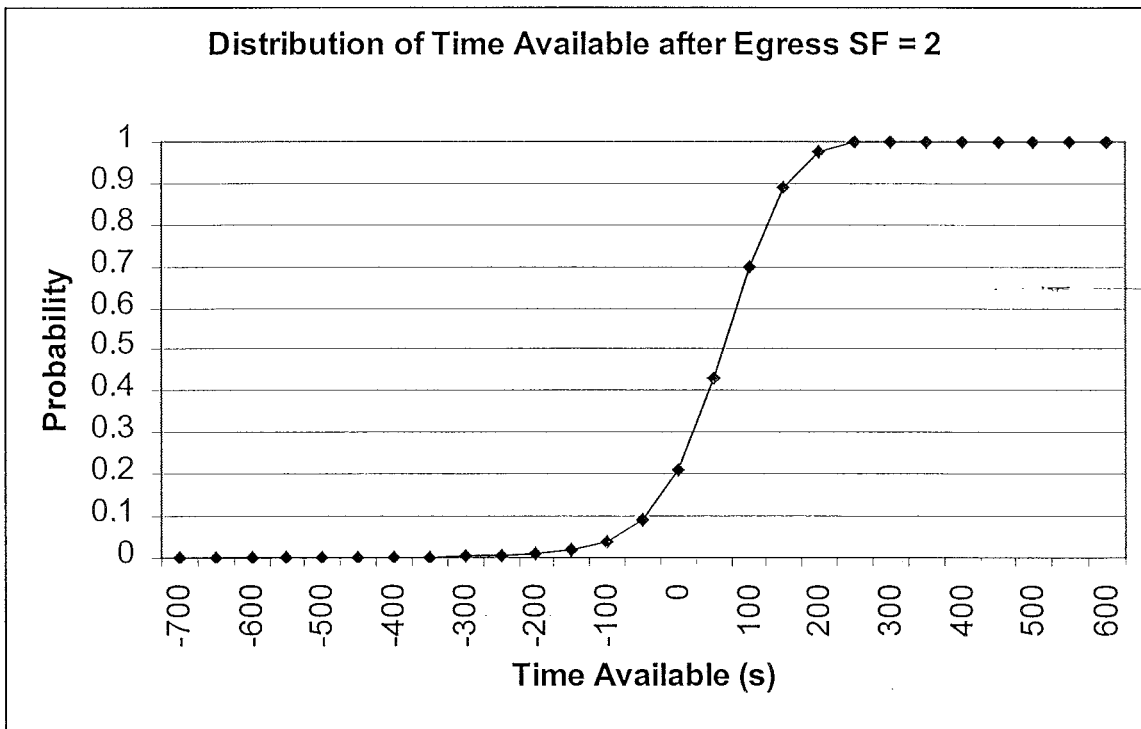
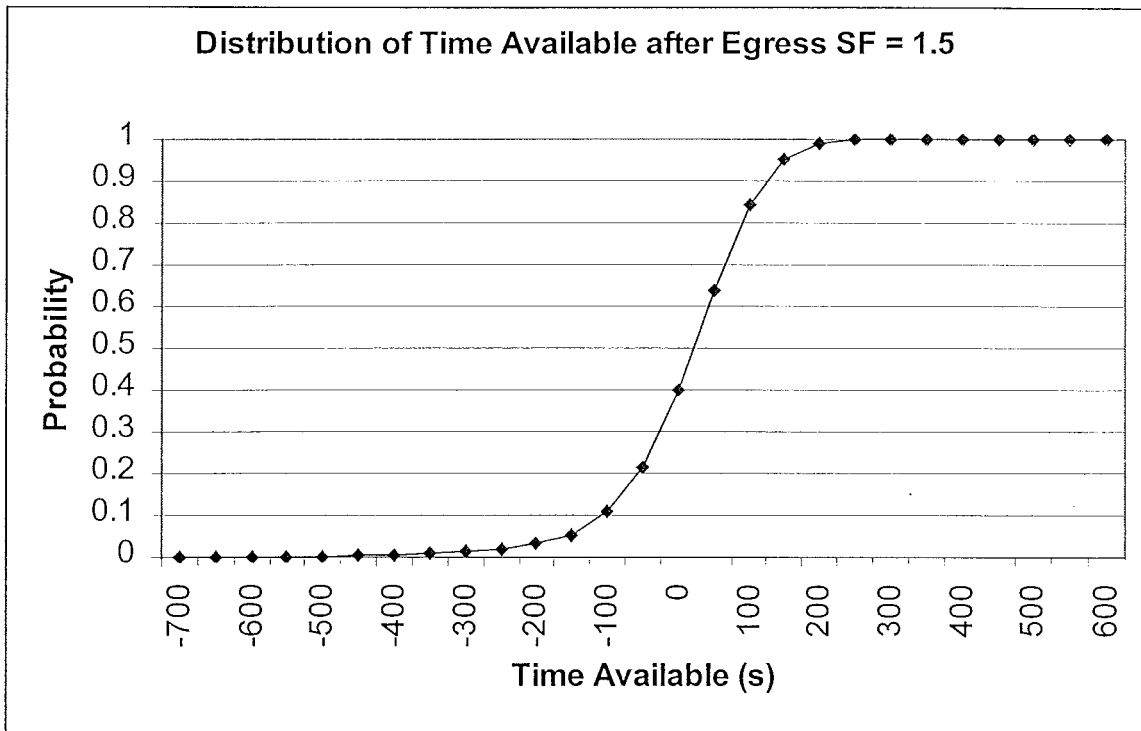


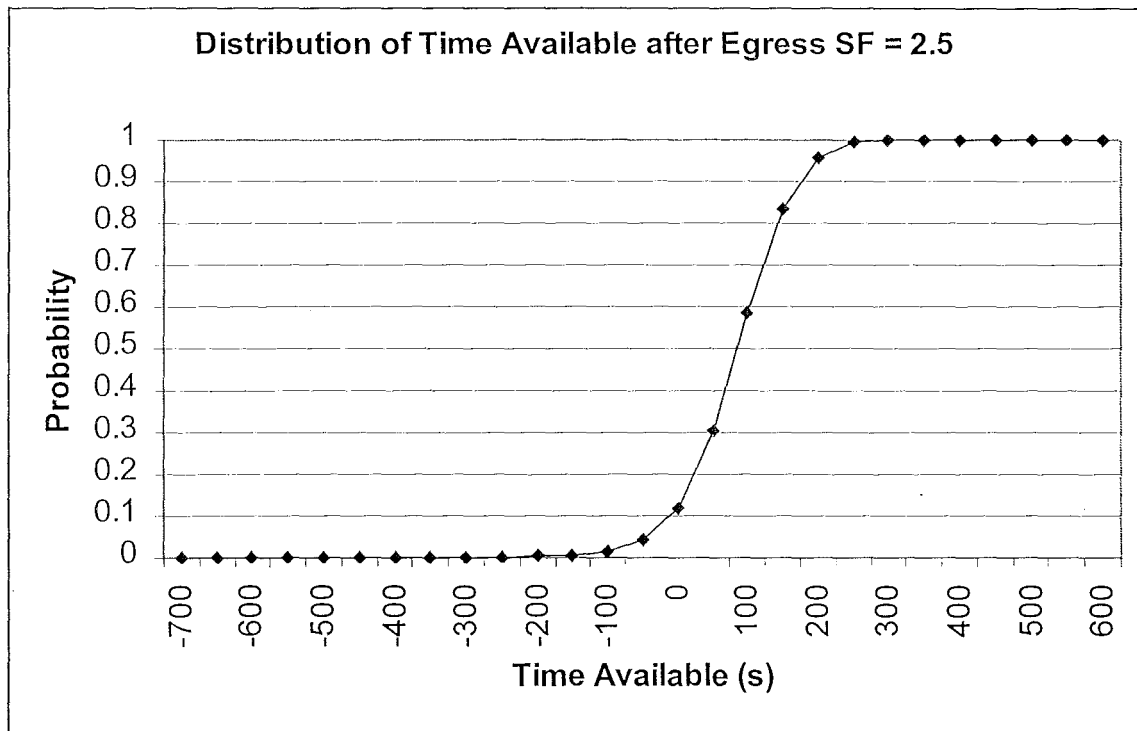




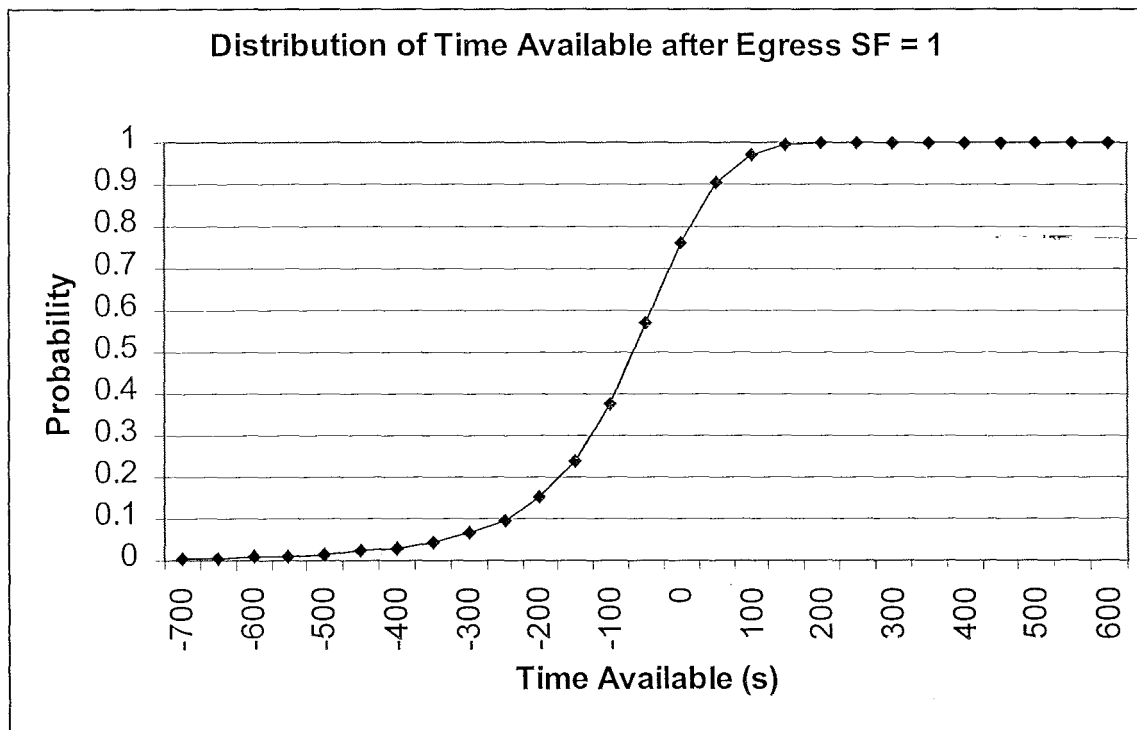
Scenario 7 – Fast occupant travel speed

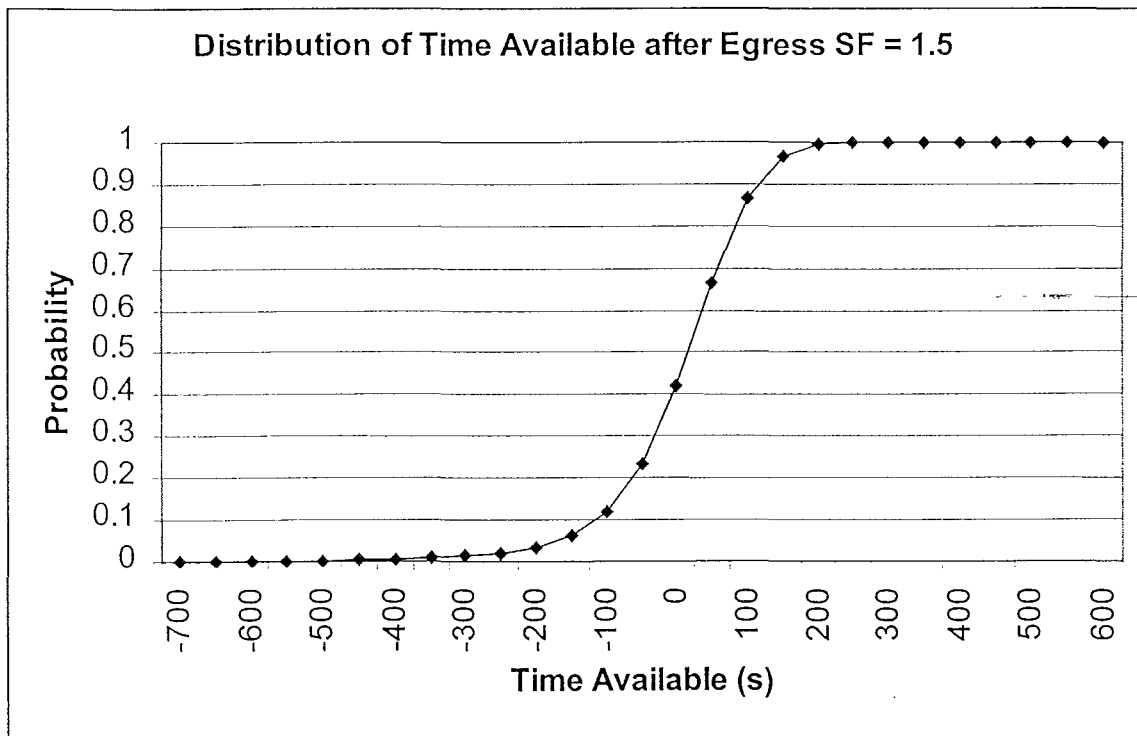
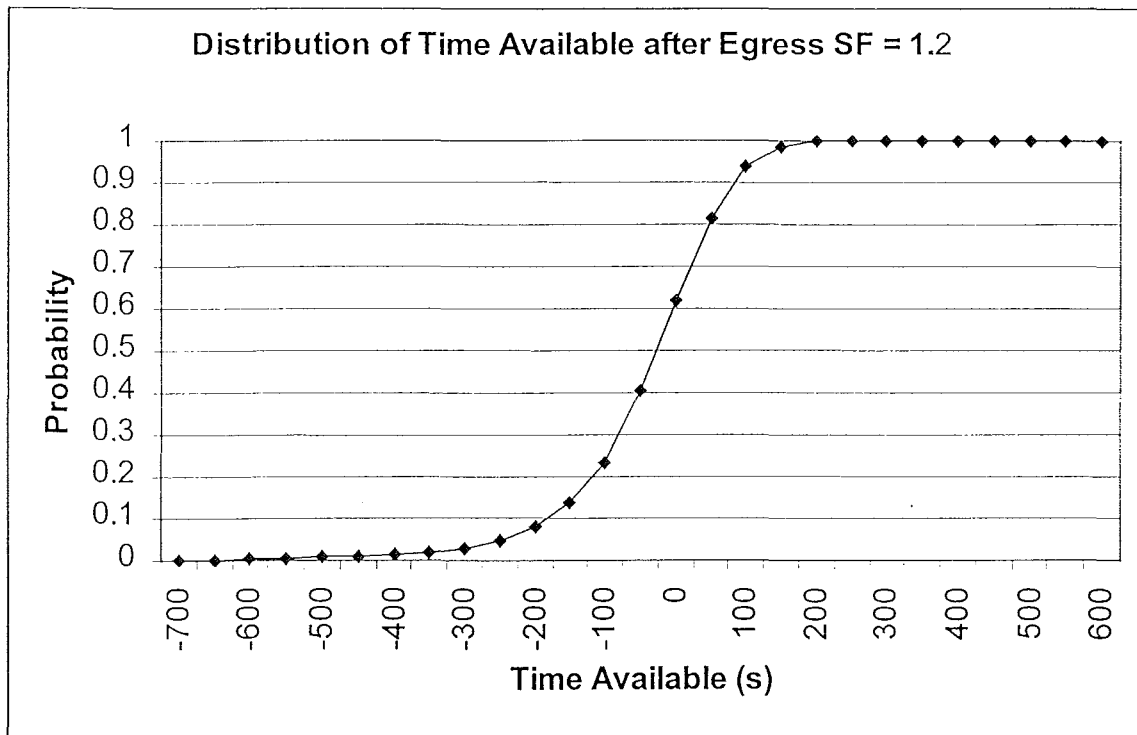


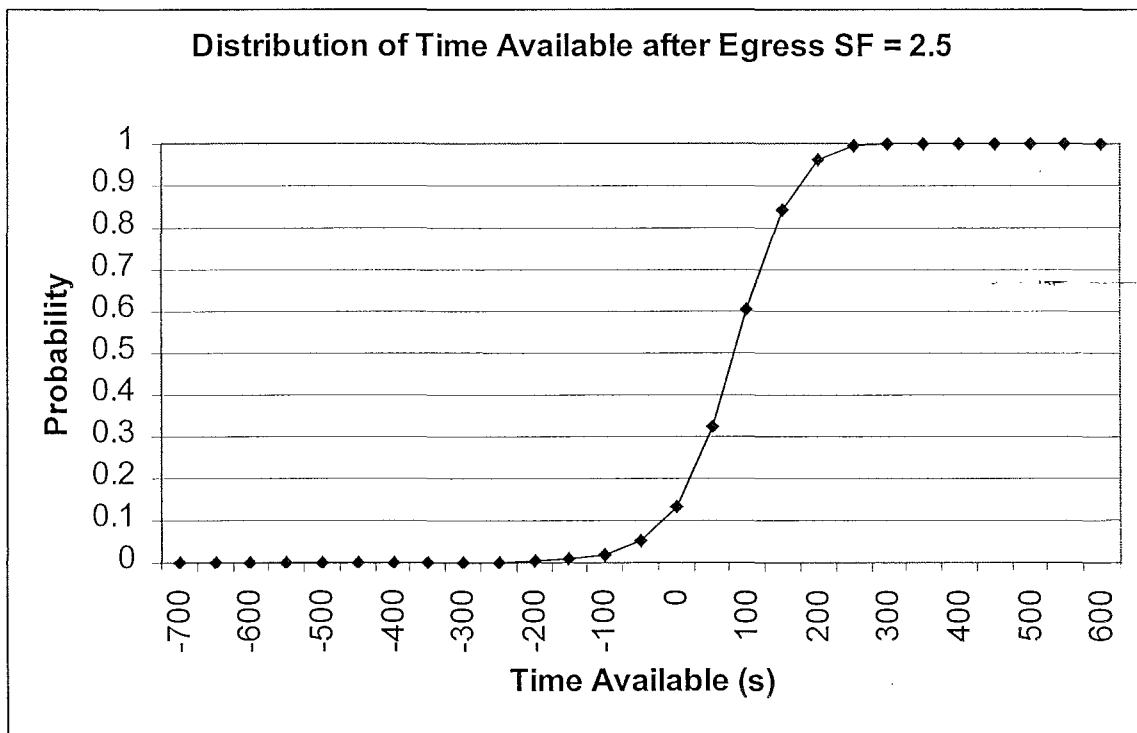
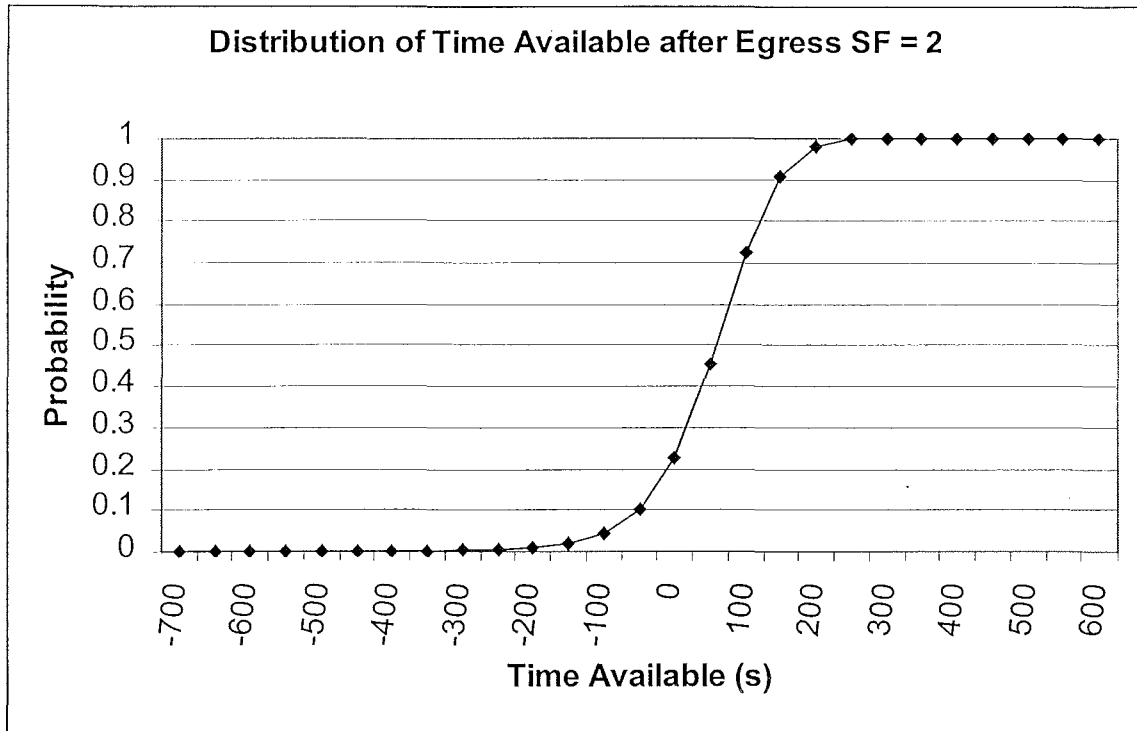




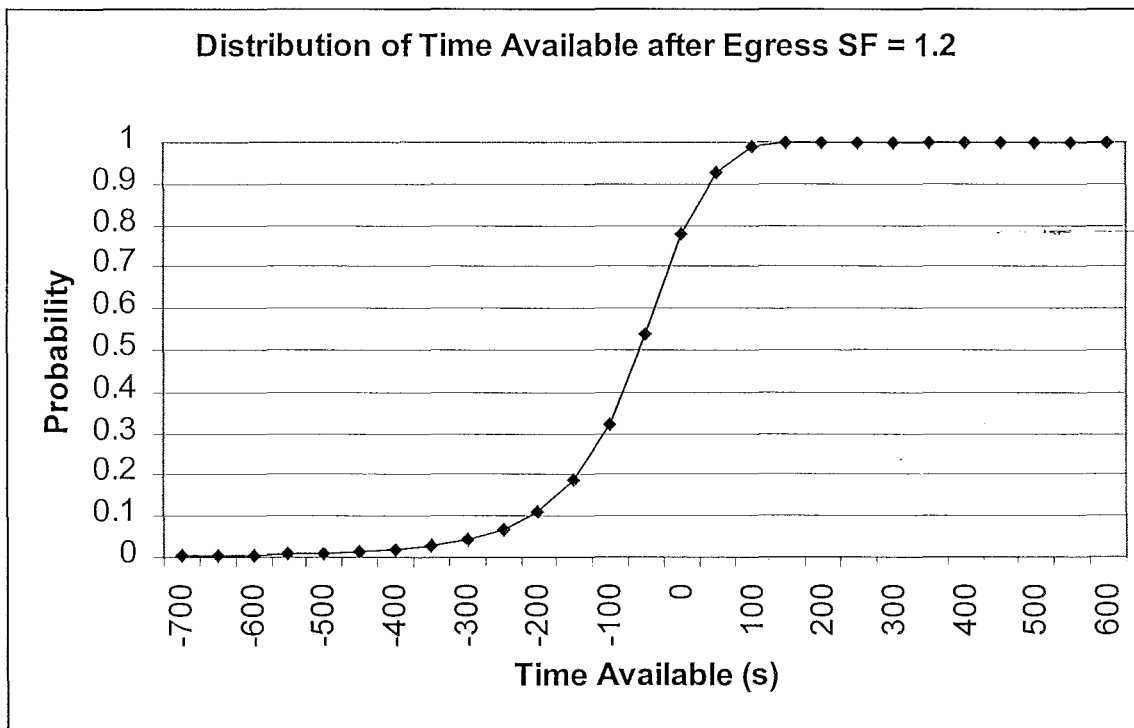
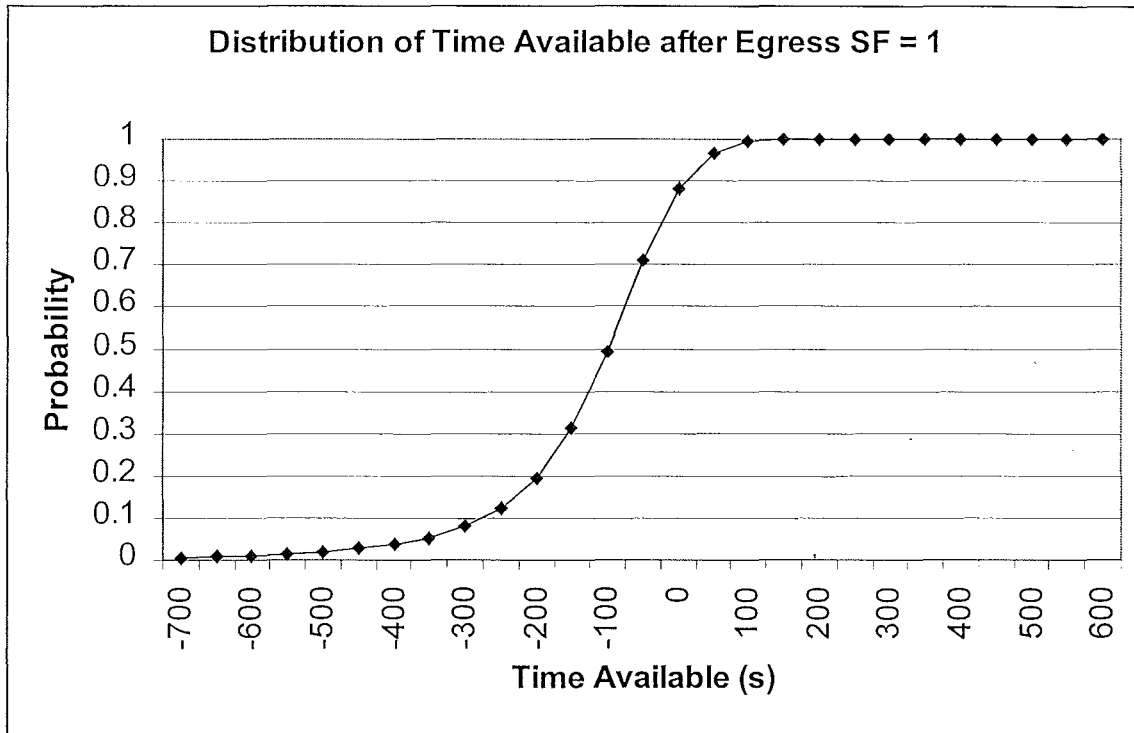
Scenario 8 – Slow occupant travel speed

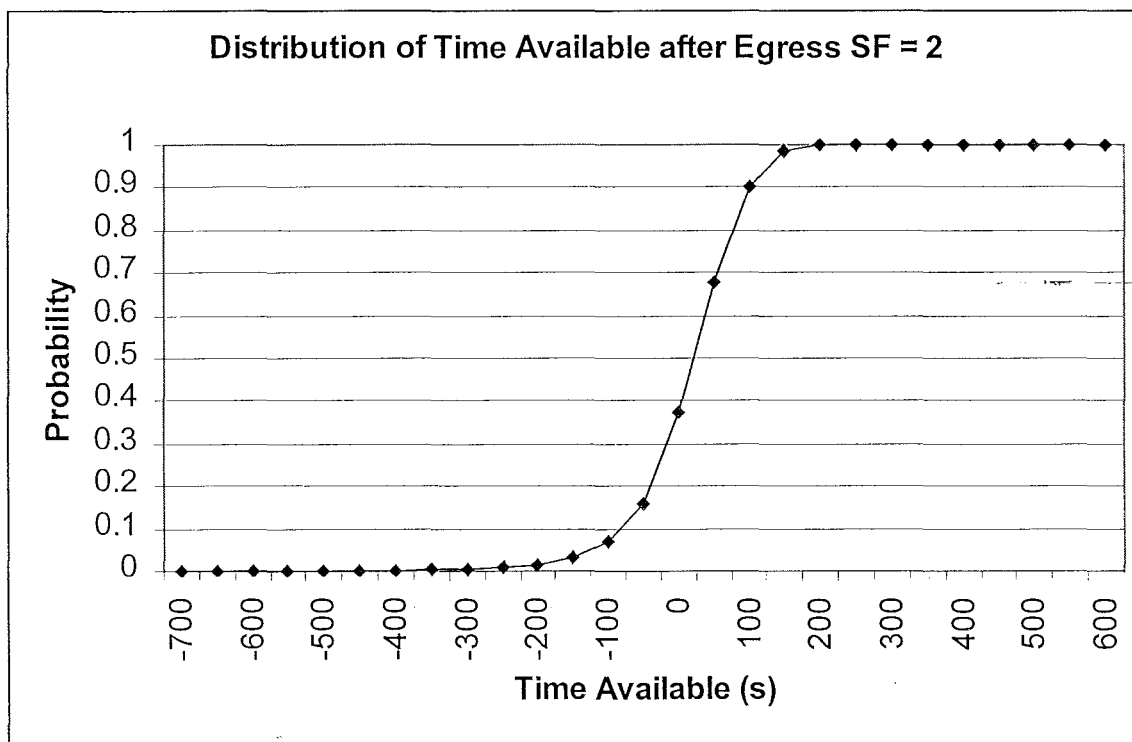
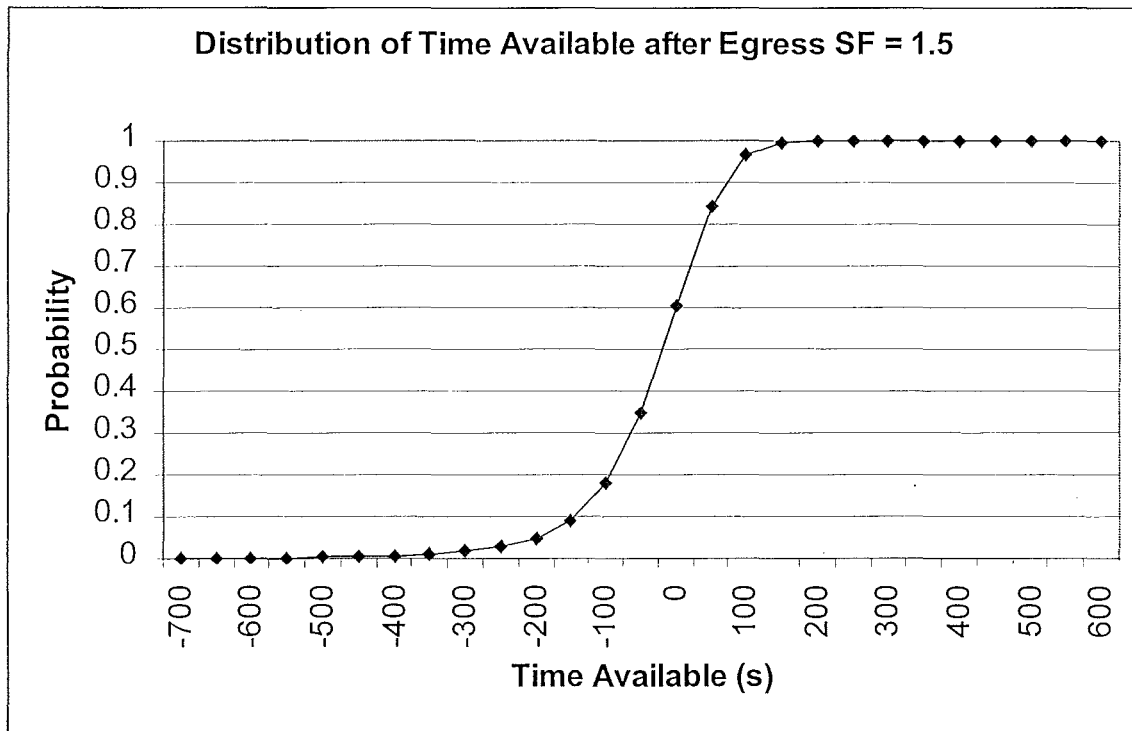


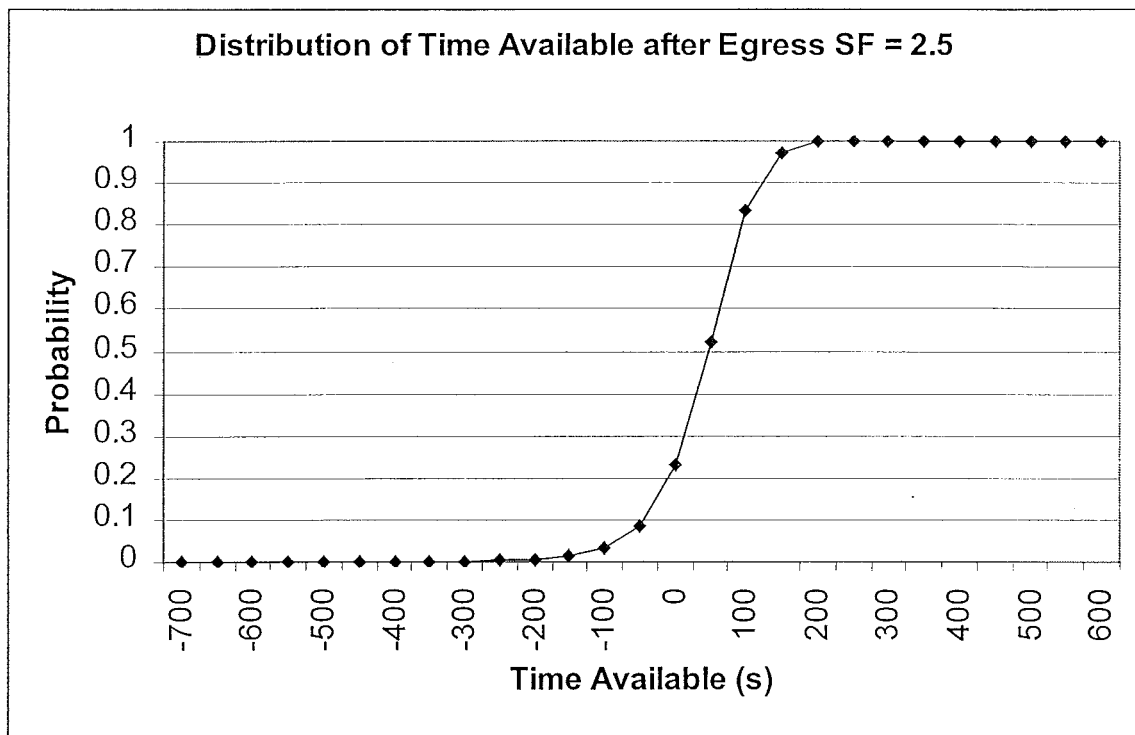




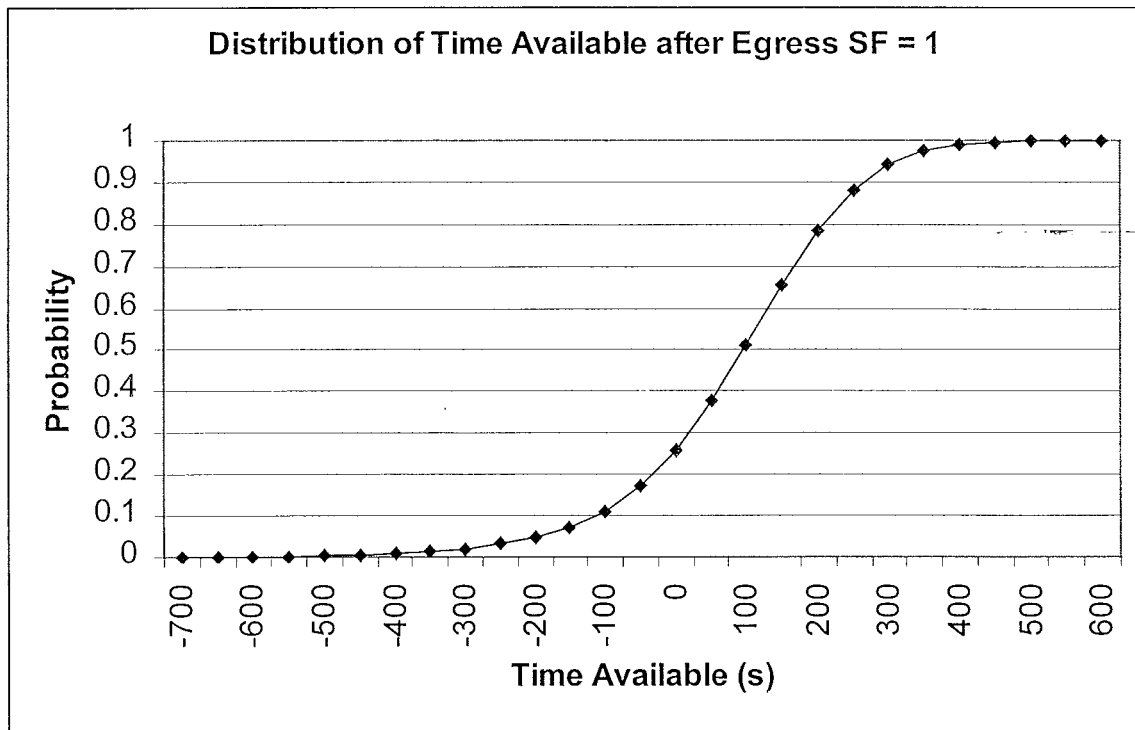
Scenario 9 – Smoke layer height used as tenability limit

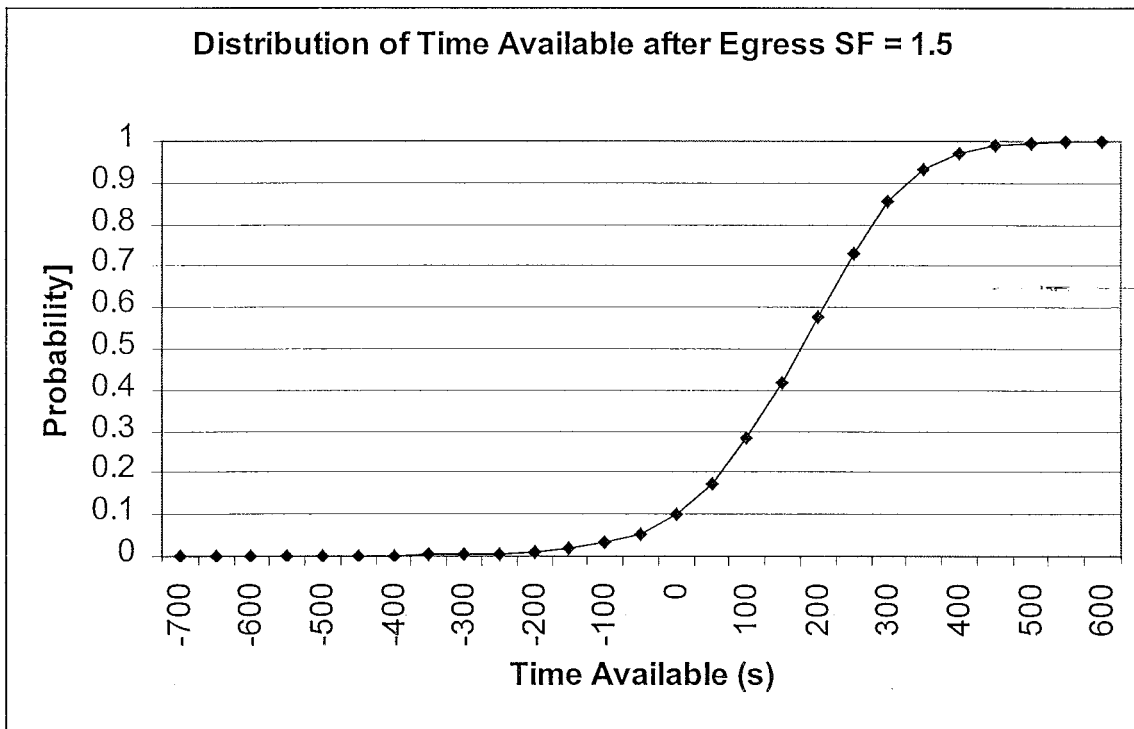
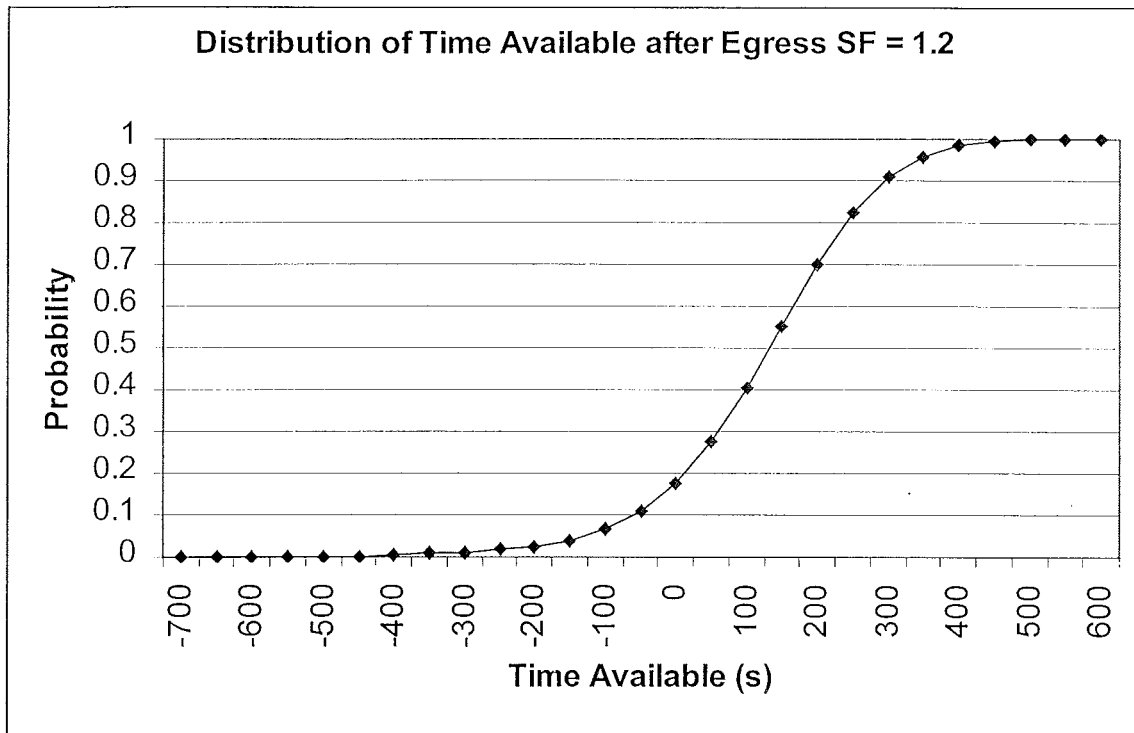


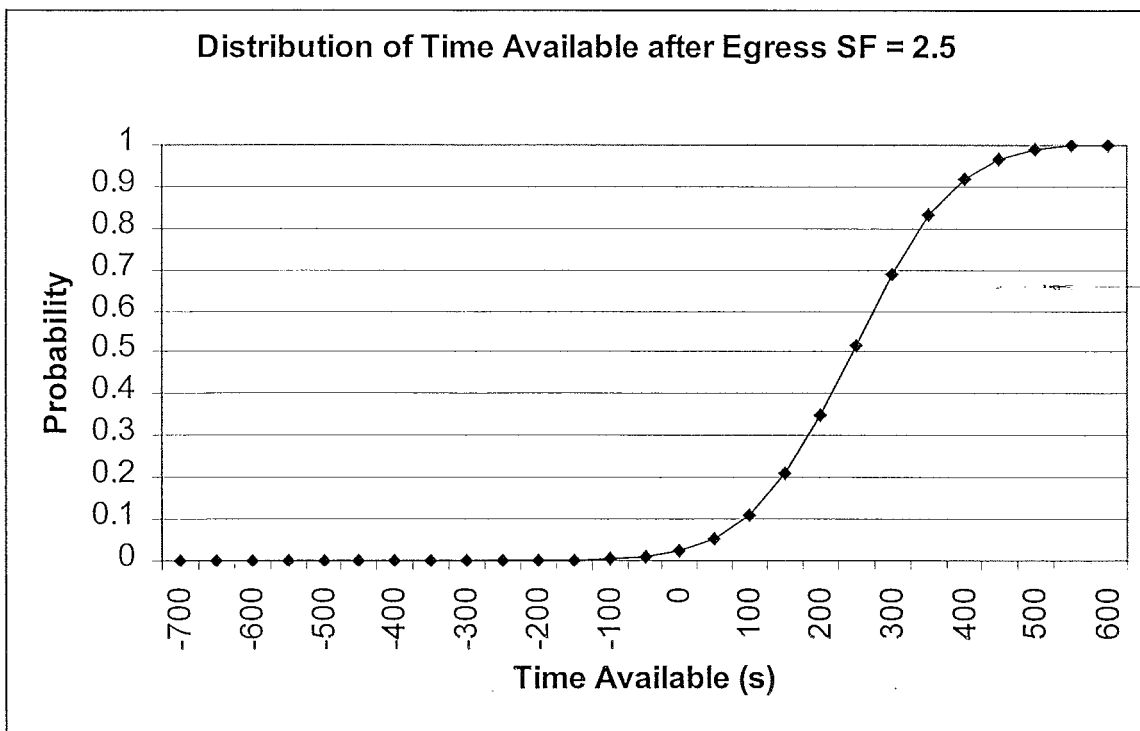
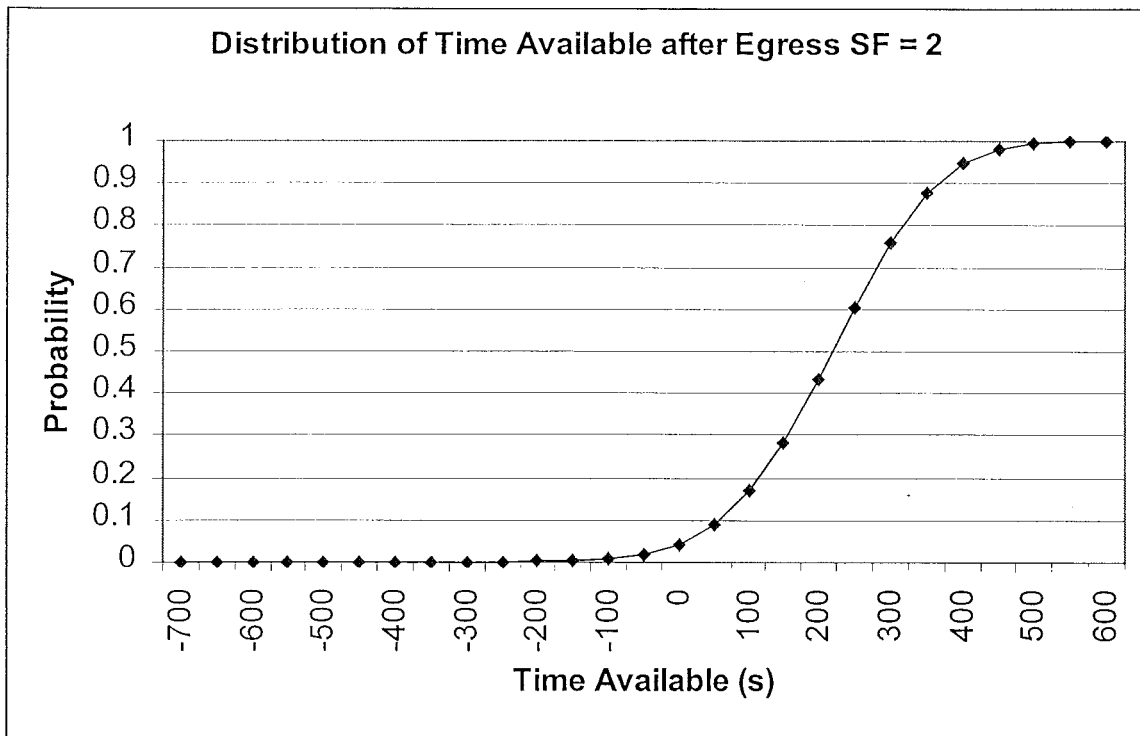




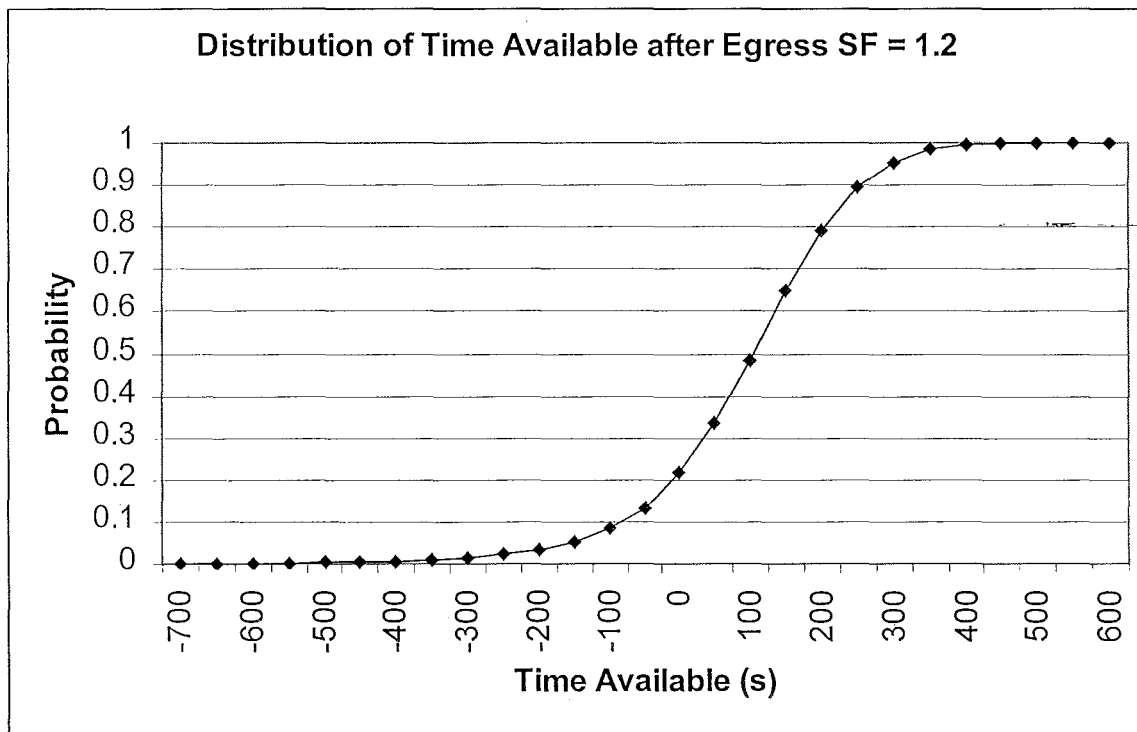
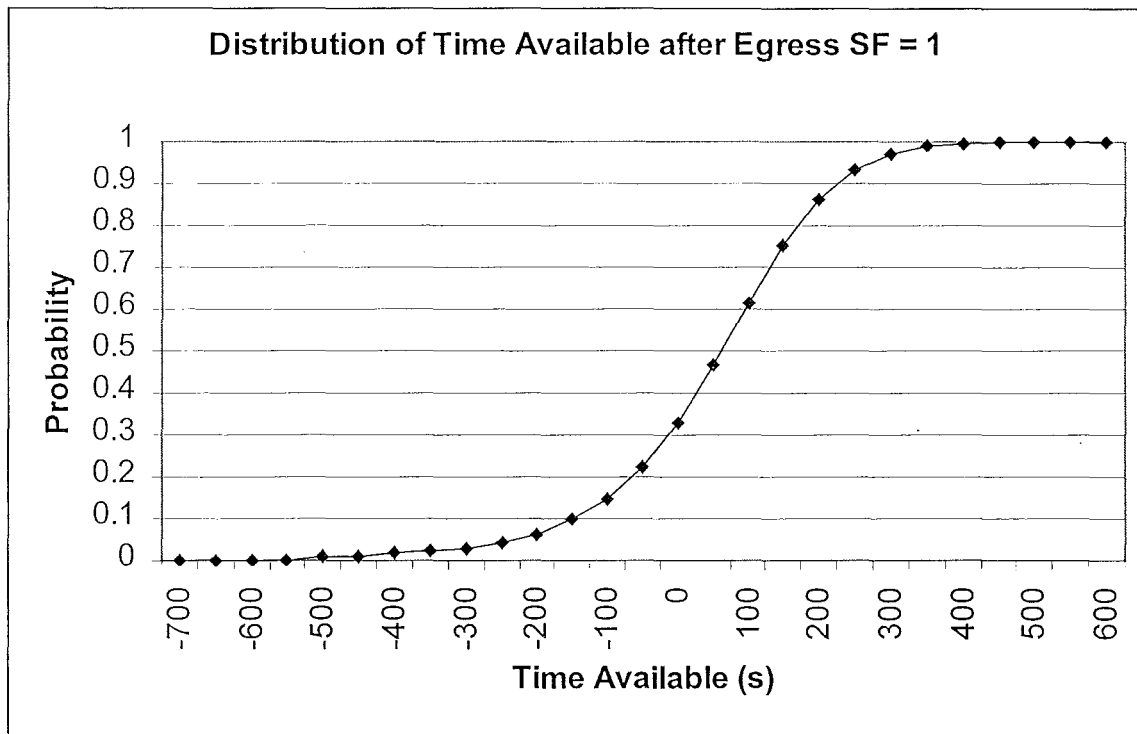
Scenario 10 – Fractional equivalent dose (FED) used as tenability limit

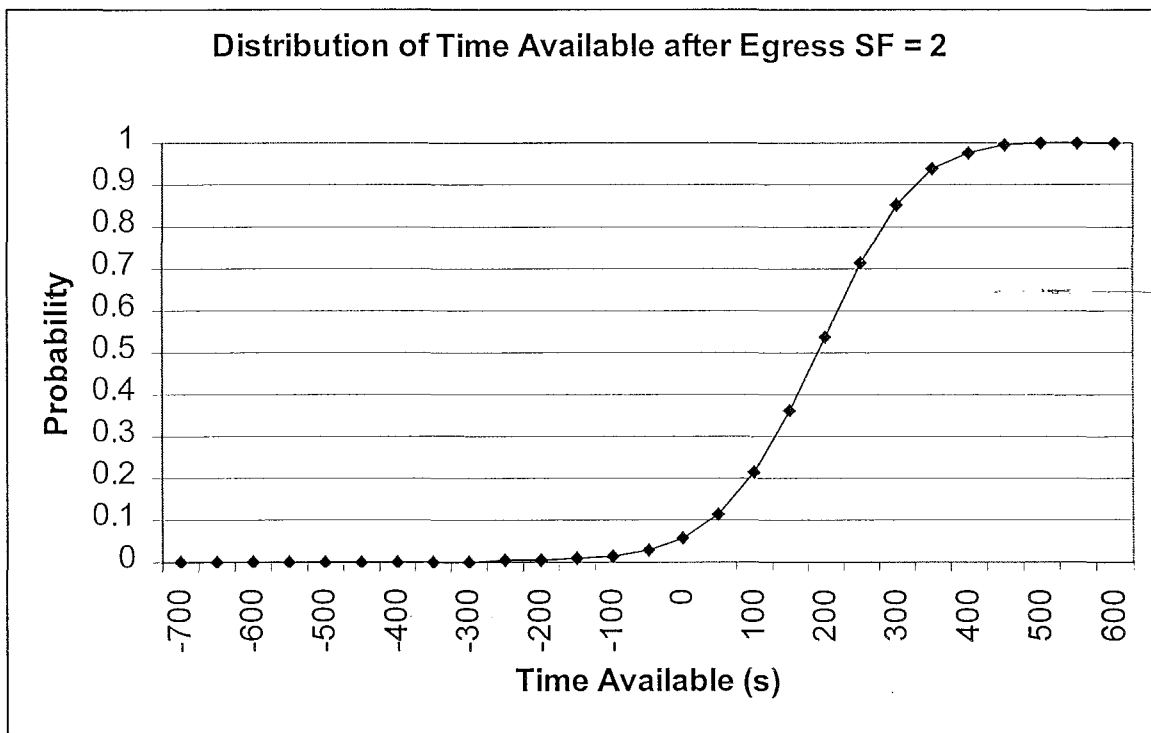
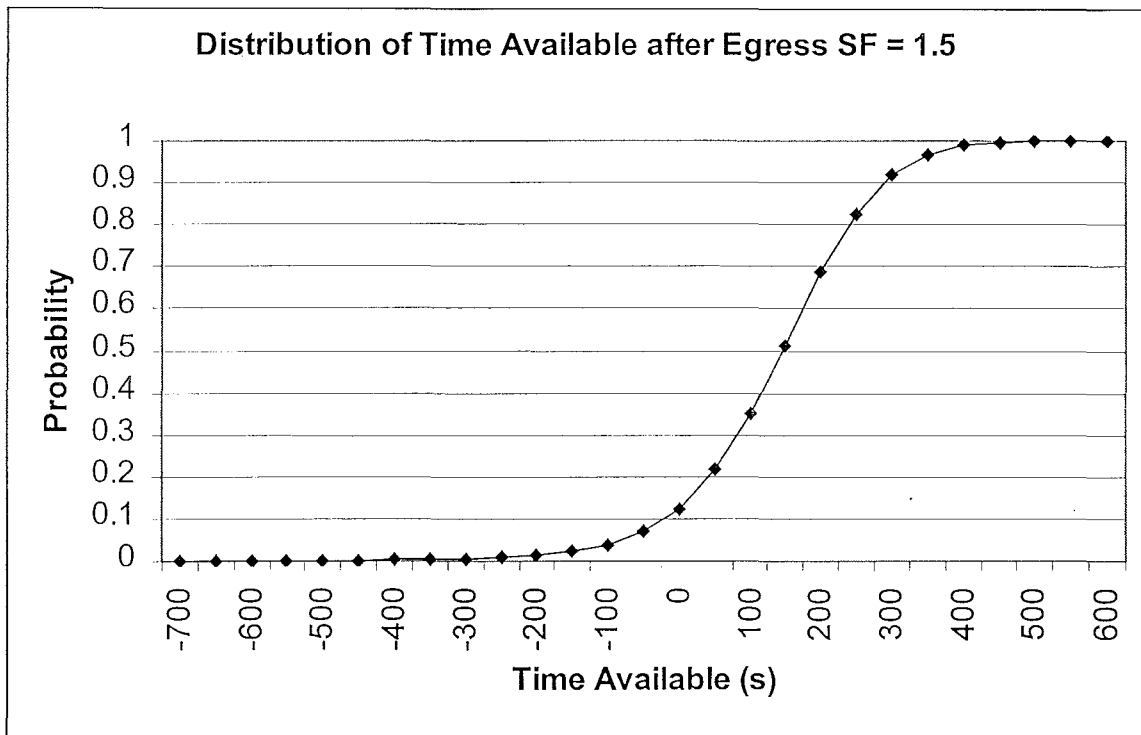


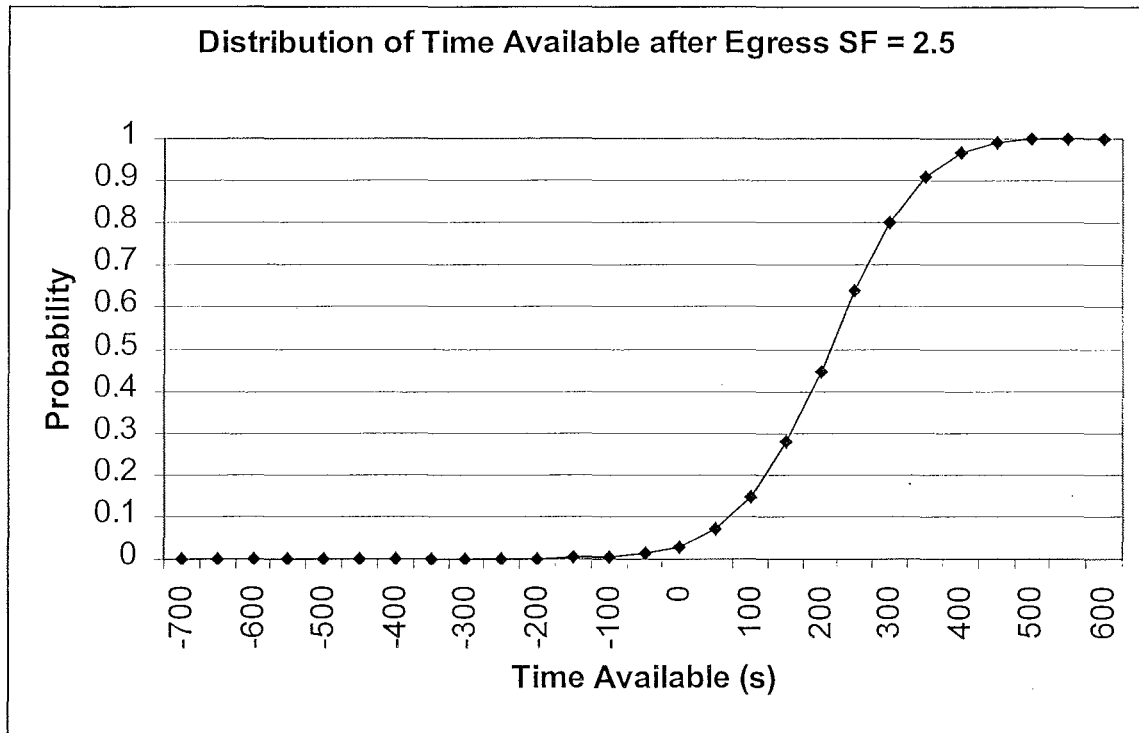




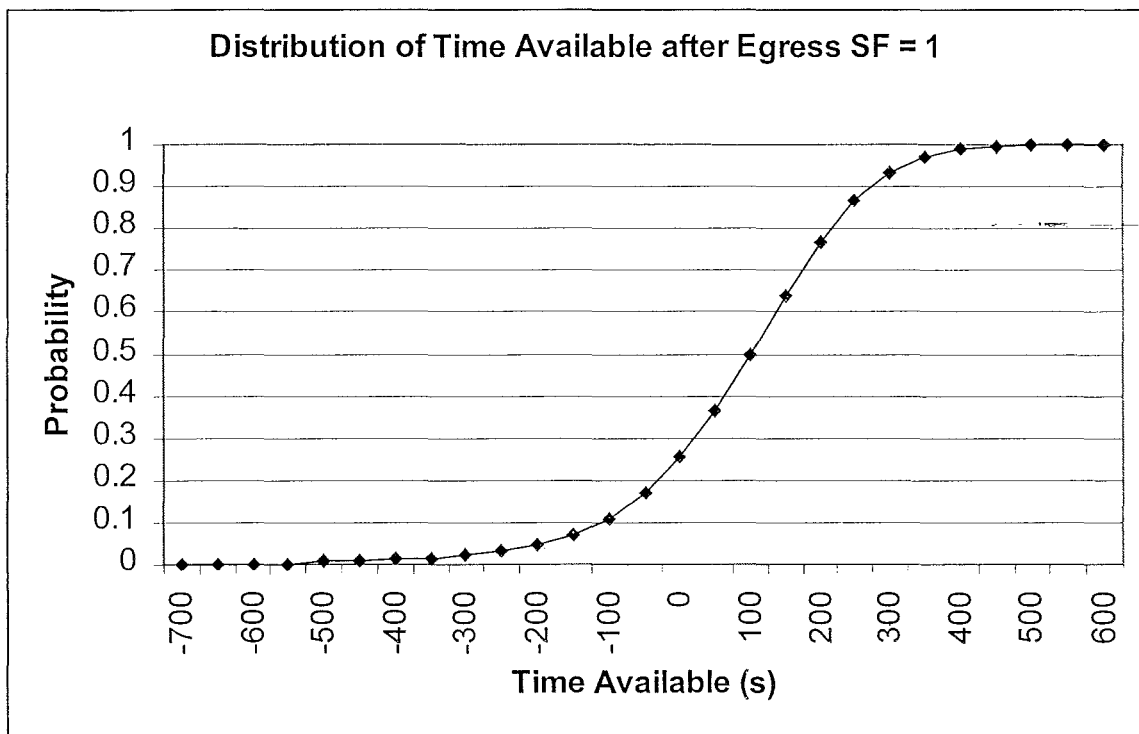
Scenario 11 – Medium ventilation used

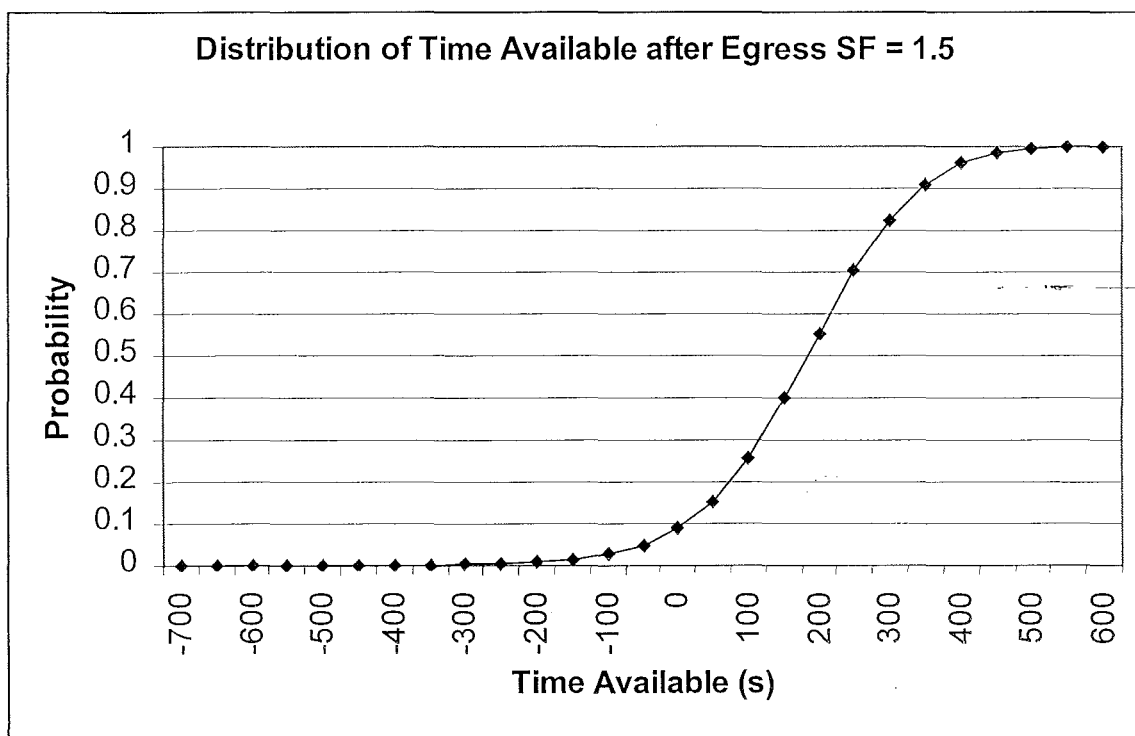
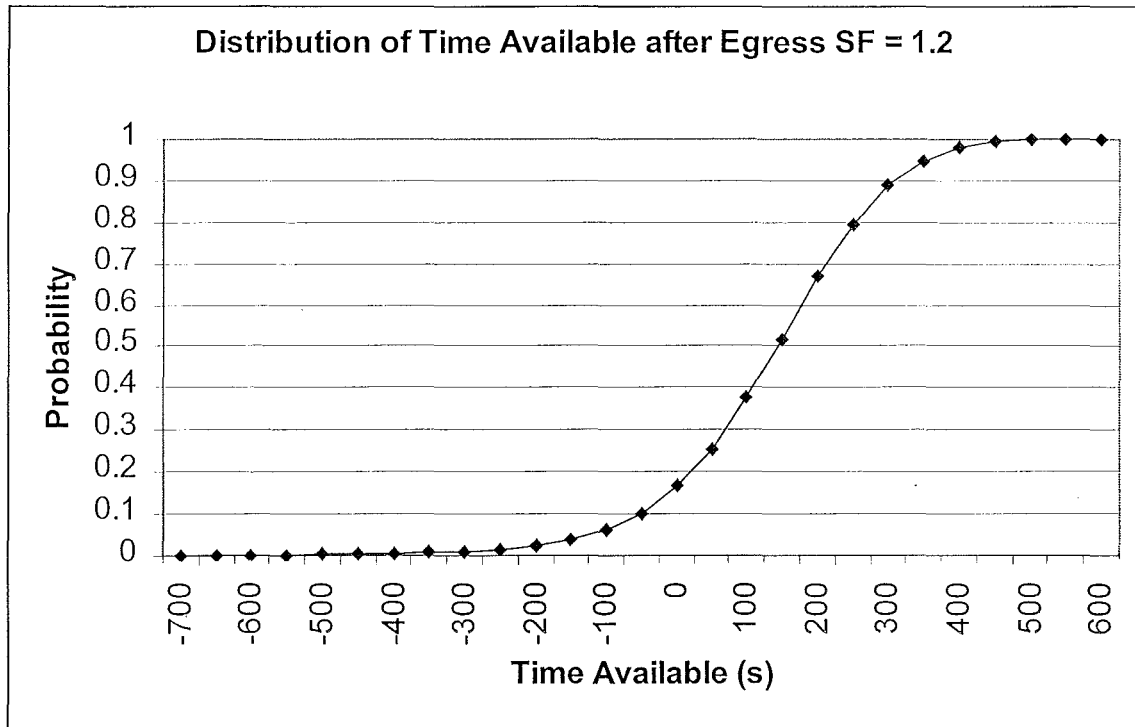


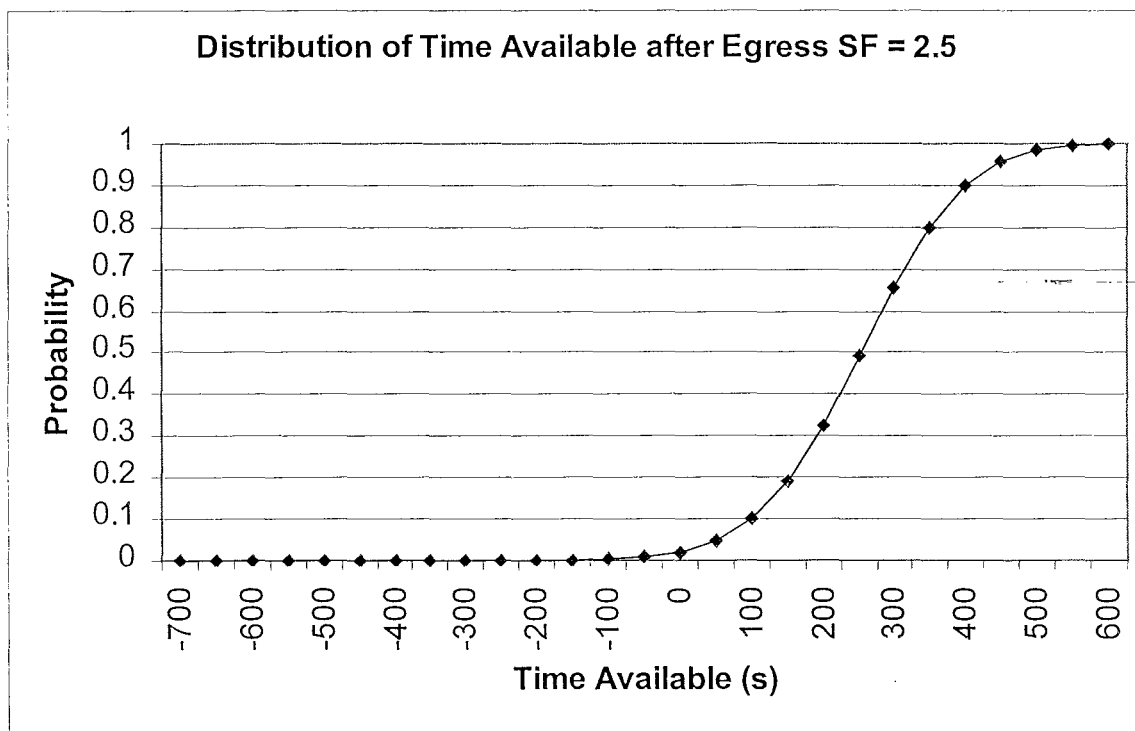
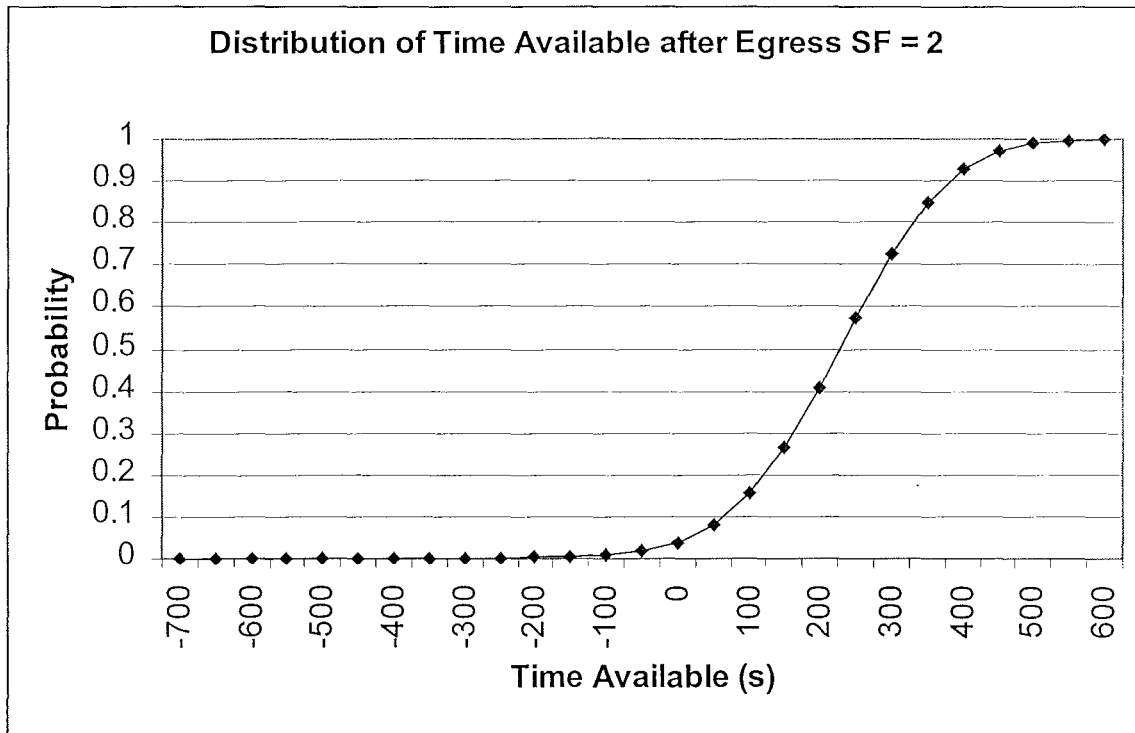




Scenario 12 – High ventilation used







Appendix B

@RISK Characteristics

Effect of differing random seeds

A comparison of random seeds versus two different levels of iterations was made. There was some level of variation between random seeds, as would be expected with pseudo-random numbers. The difference between the use of 5000 and 10,000 iterations in @RISK was significant to the accuracy of the simulation. This comparison was made without the use of Latin-Hypercube sampling in the simulation.

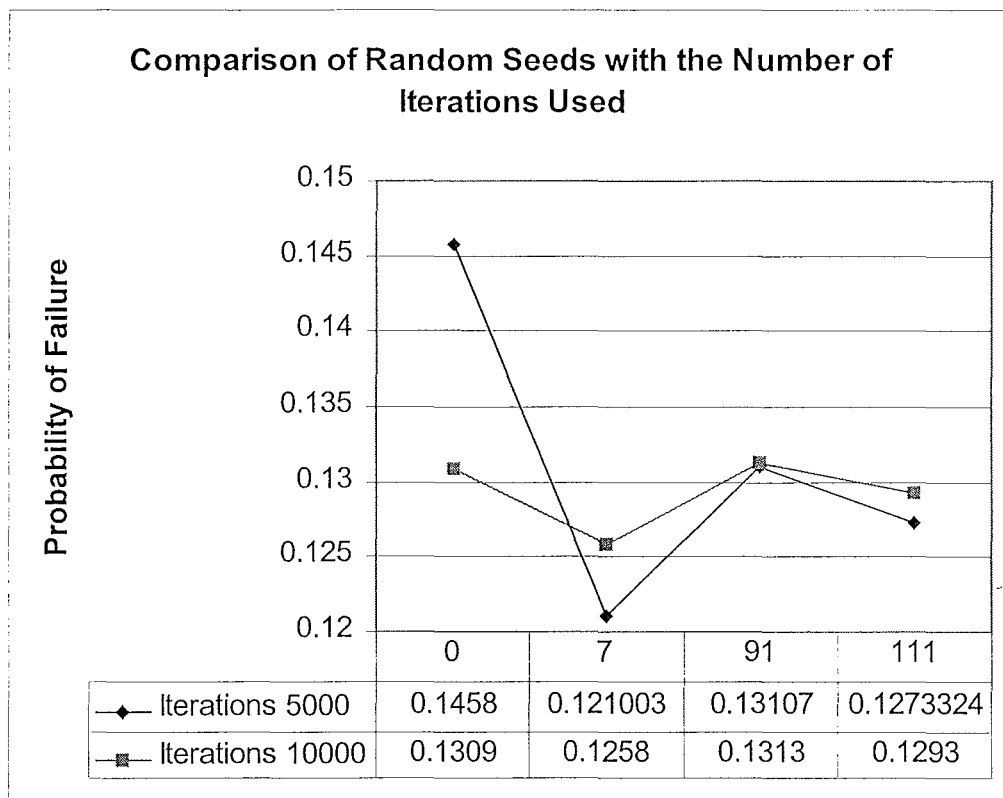


Figure 11 Effect of differing random seeds and number of iterations

Looking at figure 10, the result of the simulation for 10,000 iterations has a reasonably linear result, whereas 5000 iterations produced some larger differences within the simulation. The variation between differing random seeds is less. So the usage of 10,000 iterations in all simulations was selected.

All the input distributions were the same, only the random seed and the iterations were varied.

Appendix C

Spread sheet model used formulae/numerical versions

	A	B	C	D	E	F	G	H	I
1	Evacuation Time (s)	Mean	C.O.V.	Distribution	Ttravel			mean (m/s)	standard deviation (m/s)
2	Tdetection	130	0.3	=RiskTnormal(B2,(B2*C2),0,2500)	Distance to Travel	20	m		
3	Tactivation	0	0	0	Velocity	1.5	m/s	1.5	0.1
4	Tresponse	130		=RiskTlognorm(B4,120,0,2500)					
5	Ttravel			=F2/F3					
6									
7	Safety factor used	1							
8	Safety margin factor	1.5							
9	Safety margin used (s)	=D11*(1-(1/B8))							
10									
11	Total travel time			=SUM(D2:D5)*(1/\$B\$7)					
12	Modified travel time with safety margin			=D11-B9					
13									
14	Untenability time	190	0.3	=RiskNormal(B14,(B14*C14))					
15									
16	Time available to escape (s)	=D14-D12							

	A	B	C	D	E	F	G	H	I
1	Evacuation Time (s)	Mean	Coefficient of Variation	Distribution	Ttravel			mean (m/s)	standard deviation (m/s)
2	Tdetection	130	0.3	130.049729	Distance to Travel	20 m			
3	Tactivation	0	0	0	Velocity	1.5 m/s	1.5		0.1
4	Tresponse	130		129.1293598					
5	Ttravel			13.33333333					
6									
7	Safety factor used	1							
8	Safety margin factor	1.5							
9	Safety margin used (s)	90.83747403							
10									
11	Total travel time			272.5124221					
12	Modified travel time with safety margin			181.6749481					
13									
14	Untenability time	190	0.3	190					
15									
16	Time available to escape (s)	8.325051945							

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